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February 1994

Intentionally Short-Range Communications (ISRC)

1993 Report

J. Yen
P. Poirier
M. O'Brien

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ADMINISTRATIVE INFORMATION

The Intentionally Short-Range Communications (ISRC) project is sponsored by the U.S. Marine Corps, Marine Corps Systems Command, under project C3125 (command, control, and communications mission area) and program element 602131M (Marine Corps Landing Force Technology).

Released by
D. M. Gookin, Head
Electro-optic Systems and
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Under authority of
C. E. Gibbens, Head
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LH

EXECUTIVE SUMMARY

OBJECTIVE

1. Perform feasibility studies of the technologies developed under the Intentionally Short-Range Communications (ISRC) project.
2. Complete test protocols for the ISRC prototype links.

RESULTS

1. Published Ti:Sapphire laser paper in November 1993.
2. Awarded three follow-on Phase II contracts in May 1993; contracts will be completed in May 1994.
3. Updated test protocols with new technical information.
4. Developing plans for the Joint Tactical Communications (JTC) Advanced Technology Demonstration (ATD).

RECOMMENDATIONS

1. Complete plans for transitioning to JTC ATD.
2. Continue to refine the test protocols for all of the ISRC technologies.
3. Evaluate results of the Phase II contracts to recommend candidate technologies for Phase III.
4. Apply the technologies developed for ISRC missions to covert and amphibious missions.

CONTENTS

APPENDICES

FIGURES

TABLES

1.0 INTRODUCTION

1.1 OBJECTIVE

The purpose of the United States Marine Corps (USMC) Intentionally Short-Range Communications (ISRC) Exploratory Development project is to demonstrate the feasibility of using one or several technologies for low probability of detection/intercept (LPD/LPI) short-range data transmissions. The feasibility demonstration is expected to transition into the Joint Tactical Communications (JTC) Advanced Technology Demonstration (ATD).

A satisfactory technology may be range-limited based on the physical properties of the atmosphere and the propagation medium. Such a link has an inherent LPD capability.

An alternative scheme is spread spectrum technology, which distributes the signal over a wide spread bandwidth. The result is that the signal is hidden in the noise.

1.2 SCOPE

This report encompasses the development, fabrication, and testing of several candidate technologies during Fiscal Year 1993 that have the potential of satisfying all three of the ISRC missions: Company Radio, Local Area Network (LAN) Backbone, and Wideband Data Link.

Appendix A describes the upgraded test protocols, or requirements, that each of these prototype links must satisfy in order to be considered a viable ISRC system for transitioning to the JTC ATD.

Appendix B contains the professional paper describing the work performed with respect to the tunable Ti:Sapphire laserhead development.

Appendices C through F summarize the awarded Phase I contracts (four) and Phase II contracts (three).

1.3 KEY PERSONNEL

Major Paul Gibbons, Marine Corps Systems Command (MARCORSYSCOM) Code AW, (703) 640–2761, DSN 278–2761.

Mr. John Yen, NRaD Code 843, (619) 553–6502, DSN 553–6502.

2.0 BACKGROUND

2.1 MARINE CORPS REQUIREMENTS

The USMC expressed interest in developing communications links with ranges intentionally limited to very short distances. These links are described below. The development of these ISRC links is discussed in NRaD Technical Document 2286 (Yen, 1992) and NRaD Technical Report 1600 (Yen et al., 1993). This report contains the progress to date of the ongoing feasibility study.

2.1.1 Company Radio

The Company Radio is a very short-range (≤0.5 km), omnidirectional, low-data-rate (2400 bps), vehicle-mounted, mobile voice link for use in a company or a platoon. Possible applications of the Company Radio include an urban warfare communicator and a landing zone communicator.

2.1.2 LAN Backbone

The LAN Backbone is a short-range (≤1.0 km), semidirectional, low- (2400 bps) to high- (1.6 Mbps) data-rate, transportable data link for connecting several LANs. The LANs range from the low-data-rate LAN bridges to high-data-rate full LANs and wide-area networks (WANs).

2.1.3 Wideband Data Link

The Wideband Data Link is a medium-range (3 to 5 km), directional, vehicle- or fixed-mounted, high-data-rate and traffic (≥1.6 Mbps or T1) link for connecting command posts (CPs) with the antenna farm.

2.1.4 Signal Detection

Most current communication systems (such as radio) have the r^{-2} signal attenuation typical of electromagnetic radiations. This means that while our encrypted transmissions cannot be understood, the enemy can still detect their presence, direction find (DF) on them, and take countermeasures. This is a tactical threat to our ground forces.

2.2 ISRC TERMINOLOGY

2.2.1 Link Definitions

Link type definitions in this report follow below:

Omnidirectional:	signal is sent in all directions azimuthally
Semidirectional:	signal is sent into an azimuthal quadrant (±45 degrees)
Directional:	transmitter direction within ±5 degrees of the receiver
Line–of–sight (LOS):	within ±1 degree
Strictly LOS (SLOS):	within ±0.01 degree
Non–LOS (NLOS):	no LOS between transmitter and receiver

2.2.2 LPI and LPD

Low probability of intercept (LPI) means that the enemy has a low likelihood to intercept and understand our transmissions. An encrypted link is LPI but still may be detectable by enemies.

Low probability of detection (LPD) means that the enemy has a low likelihood to detect and direction find our transmissions. An LPD system is inherently LPI.

2.2.3 Broadband and Wideband

In this document, "broadband" is defined as a broad spectrum of wavelengths, as distinguished from "wideband," which is a wide range of data rates.

2.2.4 Spread Spectrum

Two techniques are commonly called "spread spectrum": direct sequence and frequency hopping.

In direct sequence spread spectrum (DSSS), the carrier is modulated by a wideband pseudorandom (or pseudonoise) sequence that spreads the signal over a large instantaneous bandwidth. The resultant bandwidth equals the bandwidth of the pseudorandom sequence, which is many times greater than the data bandwidth; thus individual components are below the noise.

In frequency hopping, the instantaneous bandwidth of the signal equals the data bandwidth, but the carrier frequency is hopped over a pseudorandom sequential set of frequencies whose aggregate bandwidth is many times greater than the data bandwidth. Therefore, this signal is detectable if the receiver happens to be at the correct frequency at the correct time.

2.3 HISTORY

The history of communications is replete with attempts to increase the operational range. The ISRC program and its predecessor are the first systemic efforts to develop a tactical communications system whose range is deliberately limited. This program encompasses several technologies, such as solar-blind ultraviolet (UV) light, infrared (IR) light, millimeter waves (MMW), and spread spectrum.

2.3.1 UV

Communications that use UV light in the solar-blind region were proposed by Sunstein (1968), Reilly (1976), Kolosov et al. (1976), and Junge (1977).

2.3.1.1 Early Efforts. In the late 1970s, the Army (Ross, 1978) and the Navy (Fishburne et al., 1976; Neer and Schlupf, 1978 and 1979) developed the first actual UV communications systems. These early development efforts were based on broadband UV lamps and indicated the requirement for an efficient UV emitter.

2.3.1.2 NOSC Efforts. In the 1980s, the Naval Ocean Systems Center (NOSC) developed a short range, 2400-bps, computer-to-computer link for the USMC (Geller et al., 1985 and 1986; Johnson, 1986; Yen, 1987). This link used efficient (20% conversion to UV at 254 nm) single–wavelength germicidal lamps for the UV source.

Concurrently, NOSC developed a short-range, 2400-bps, data link to transfer Carrier Aircraft Inertial Navigation System (CAINS) data from the carrier to its aircraft (Nuyda, 1986; Yen, 1987). This NOSC-developed link also used single-wavelength germicidal lamps for the UV transmitters.

The feasibility of UV radiation for longer range links was studied (Yen and Moberg, 1988). This study indicated that several disadvantages must be resolved to make a practical UV link. The interference by fires, flares, explosions, welding, and lightning must be countered. The range limitations caused by heavy fog, smog, rain, and smoke must also be characterized.

2.3.1.3 Recent Efforts. Currently, NRaD is conducting a feasibility study of the ISRC links. Several of these efforts are based on UV light, such as the NRaD Ti:Sapphire laser link (see appendix B: Poirier and Hanson, 1993), the Mission Research Corporation Nd:YAG laser link (appendix D), and the Sparta UV lamp link (appendix E).

The United States Air Force Wright Laboratory (WL) has an ongoing effort to develop a short-range air-to-air communicator for refueling scenarios based on UV light technology.

2.3.2 IR

Several efforts based on IR lasers were short-ranged by happenstance. The only previous effort known to the author to deliberately limit IR communications range was a proposal in the mid-1980s. This attempt to develop an IR laser system, with the wavelength in an absorption band, was also to support CAINS.

Recently, NRaD/MARCORSYSCOM funded Titan Systems to perform a feasibility study of an IR laser diode communications link that takes advantage of the 1.39-μm water-absorption band (appendix F).

2.3.3 MMW

Efforts based on MMW, or extremely high-frequency (EHF) radiation or microwaves, were short-ranged by chance. Two previous efforts to deliberately limit range with MMW are known to the author. The first effort to develop a portable short-range communicator was in the early 1980s (Hislop, 1982). The other was a proposal in the mid-1980s to develop a MMW system taking advantage of the 60-GHz oxygen absorption band in order to support CAINS.

Recently, MARCORSYSCOM and the United States Army Communications Electronics Command (CECOM) funded several efforts to develop tactical communications links where the range is limited by absorption of MMW in the atmosphere.

2.3.4 Spread Spectrum

Spread spectrum communications systems were developed for their LPI characteristics in order to provide communications security. Range and presence detection were secondary concerns initially, but warfare doctrine and spread spectrum technology have developed to the point where such issues are being examined in depth by various activities.

Currently, NRaD/MARCORSYSCOM is funding an effort by GTE to develop a direct sequence spread spectrum (DSSS), short-range, LPD/LPI communications link. Industry and many other activities such as the National Security Agency and Wright Laboratory have also been involved in advancing spread spectrum technology.

3.0 APPROACHES

Four general classes of communication systems have been proposed and developed to achieve LPD/LPI: absorptive media, subnoise signals, burst mode, and angle-limited.

3.1 ABSORPTIVE MEDIA

A link whose range is physically limited by its atmospheric propagation characteristics will be inherently LPD. There are at least three media in which the link range is limited by the propagation physics: UV light, IR light, and MMW.

3.1.1 UV LIGHT

UV light in the solar-blind spectral region (200 to 300 nm) is strongly attenuated by ozone molecules in the atmosphere. The ozone layer in the upper atmosphere absorbs essentially all of the solar UV radiation in the solar-blind region, so that there is almost no solar background in this spectral region (Yen, 1987). This low background allows the use of a very small number of scattered photons for a viable signal, resulting in a non-line-of-sight (NLOS) link.

Attenuation by the residual ozone at sea level (5 to 25 dB/km, depending on the ozone concentration) limits the range of a UV link to several (≤5) kilometers. The ozone attenuation of UV radiation also limits the detection of UV transmissions to short distances, resulting in a LPD link.

Given a receiver filter that passes radiation only in the solar-blind region and blocks all other radiations, a UV link can operate with very small received signals due to the lack of solar background.

3.1.1.1 UV Sensor. To take advantage of the solar-blind region, the receiver filter must be able to block non-solar-blind radiation very effectively. Such filters can be very expensive to make even with today's technology.

The photomultiplier tube (PMT) used in the UV Comm sensor is highly sensitive, but it is not inexpensive. Solid state UV detectors, while cheaper and smaller, have sensitivities that are orders of magnitude less than PMTs.

3.1.1.2 UV Lamp Transmitter. The UV source (germicidal lamps) used by the UV Comm system was highly efficient in outputting UV light at a single wavelength (254 nm). However, it was bulky, fragile, and restricted in data rates (≤20 kHz at short ranges). Therefore, it is not recommended for use in the ISRC missions with higher data rates.

Arc lamps are compact and easier to ruggedize, but they are broadband optical emitters, thus making them difficult to use for multichannel applications. Their output power is also not sufficient for some of the ISRC links. Finally, their IR and visible emissions can prove a detection signature unless filtered out.

UV lamps would be the easiest and least expensive to adapt for use in the low-data-rate links. This avenue would be desirable for building a feasibility demonstration prototype quickly.

3.1.1.3 UV Laser Transmitter. The use of an UV laser can increase the signal per pulse detected by eliminating much of the wasted vertical emissions and decreasing the effective detection bin size (very short laser pulses). Industry is in the process of miniaturizing the laser components and reducing the power requirements, so that UV lasers of practical sizes are now available.

They will be useful for the Company Radio and the low-data-rate LAN Backbone applications, since the short effective bin size should suppress UV noise sources. With much smaller bin sizes (5 μs versus >400 μs), the UV noise sources are expected to have time characteristics of longer duration and will be spread out over many bins and resemble a DC source. The laser "pulse" in one (or two) ON bin would then overwhelm the semiconstant noise.

However, the use of UV lasers may not be as effective for the high-data-rate LAN Backbone and Wideband Data Link. Since LOS is required for the high-data-rate links to work, the time spreading due to the multipath flux may be negligible relative to the LOS photon flux. The summed path difference may limit the data rate to the order of 100 kbps.

3.1.1.4 UV Laser Diodes. Diode-pumped UV lasers of requisite power, rate, and size are expected to be available within the next few years. Wright Laboratory has shown interest in developing such diodes, although the wavelengths of the newest diodes (300 to 350 μm) have not reached the solar-blind.

3.1.2 IR Light

IR radiation is strongly absorbed by water vapor between wavelengths of 1 and 8 μm (10 to ≥100 dB/km). IR lasers exist that can be tuned to one of the water vapor absorption regions, resulting in a very short operations range.

3.1.2.1 IR Laser. The absorption coefficient required to reduce the operational range to 0.5 to 1 km is on the order 5 to 20 dB/km, which means that a possible wavelength region required is, for example, from 1.3 to 1.4 μm. There are solid state IR laser diodes that operate in this region, such as InGaAsP (1.39 μm). These small lasers are now available (see appendix F).

3.1.2.2 Variable Range. By tuning the wavelength along an edge of the absorption band, the atmospheric absorption coefficient encountered by the signal varies, so the operational and detection ranges can be controlled.

3.1.2.3 Attenuation. A possible problem that needs to be addressed is that the absorption coefficient depends on the relative humidity, which is not a constant like oxygen content. In a desert, the daytime humidity can be so low that the IR link range may become so large as to be no longer LPD. In a tropical climate, the humidity may so limit the range as to make it impractical. Therefore, it will probably be necessary to tune, in power and wavelength, the laser to fit the varying local humidity conditions.

Similarly, rain attenuation of IR radiation may pose a problem in rainy tropical regions.

3.1.2.4 Operational Mode. The IR option also requires that the signal be strong enough to overcome solar and other types of interference, even though the water vapor present should reduce the solar noise at the operations region considerably. The noise and weak atmospheric scattering will require LOS operations.

3.1.2.5 Data Rate. IR laser diodes can be modulated at rates of the order of megabits per second (see appendix F), thus satisfying the ISRC missions' data-rate requirements.

3.1.3 MMW

MMW (a form of microwave), or extremely high-frequency (EHF) radiation, is absorbed very strongly (≈ 15 dB/km) by the molecular oxygen in the atmosphere at 60 GHz (Ippolito, 1981). The MMW range is similar to that of UV links.

3.1.3.1 Variable Range. Similar to the IR, the frequency can be tuned along the edge of the absorption band, thus varying the atmospheric absorption encountered and the range.

3.1.3.2 Omnidirectional Antenna. Through the use of a bicone antenna (two cones with their tips touching), MMW can be transmitted and received in all azimuthal directions, thereby satisfying omnidirectionality.

3.1.3.3 NLOS. The MMW link is primarily a LOS link, with no obstructions between antennas. An MMW link with omnidirectional antennas may be able to exploit multipath propagation modes when obstructions to LOS exist between terminals.

3.1.3.4 Noise. The MMW option also requires that the signal be strong enough to overcome the noise from the solar and background sources, although the molecular oxygen and water vapor present should reduce the solar noise considerably.

3.1.3.5 Attenuation. The MMW beam will suffer some loss due to water vapor (humidity). MMW will suffer considerable loss due to passage through rain (about 12 dB/km at moderate rain of 1 in/hr; Jursa, 1985), although the beam path length is small.

3.2 OTHER TECHNOLOGIES

In the course of the ISRC development effort, technologies other than the absorptive media were encountered that showed potential for short-range LPD communications. Two such technologies are spread spectrum at radio frequencies (RF) and long-cavity lasers.

3.2.1 Spread Spectrum

The direct sequence spread spectrum (DSSS) technique uses a pseudorandom sequence to spread the RF signal over a wide bandwidth, thus reducing the RF power spectral density and hiding the signal in the noise (subnoise signals). The receiver, which has the same pseudorandom sequence, knows where in the spectrum to look with a narrow bandwidth filter to reconstruct the signal.

3.2.1.1 LPD. Since the signal is broken into millions of pieces and spread out over a wide spread band, the power density at any particular frequency within the spread band will be so small as to be below the noise level. Unless the enemy is physically close to the transmitter, it would be difficult to discern its signature from the noise.

3.2.1.2 Carrier Frequency. The spread spectrum technique differs from the frequency-hopping technique, which has also been called spread spectrum sometimes. With the frequency-hopping technique, the signal is sent out completely at the carrier frequency, which is changed constantly through a pseudorandom sequence.

With the spread spectrum technique, the carrier frequency remains unchanged, but the entire spread band centered at the carrier frequency is used to transmit data. This technique can be applied to any carrier frequency, provided that frequency is high enough to support the specified spread bandwidth. In general, for high throughput rates on the order of megabits per second, the spread bandwidth should be tens of megahertz. Such a high bandwidth in turn requires that the carrier frequency should be at least 1 GHz, that is, super high-frequency (SHF) or EHF bands.

3.2.1.3 Range Extension. Unlike absorption-dependent systems, the detection range of a spread spectrum link is shorter than the operational range, thus the operational range can be increased and remain LPD. A possible application is ship-to-shore communications.

Through the use of atmospheric evaporation ducts, the range can be extended to over-the-horizon (OTH) ranges (70 to 90 kilometers) by the use of 8-GHz SHF radiation (Patterson, 1988; Rogers, 1992). Such range extension, while preserving LPD, may allow a DSSS link to connect Marine Air-Ground Task Force (MAGTF) ships to onshore forces.

3.2.2 Long-Cavity Lasers

Generally, a laser cavity consists of a laser material placed between two mirrors. Light sent into the laser material is amplified, so that light is amplified greatly as it reflects back and forth between the mirrors. One of the mirrors has some transmittance so that the laser beam will be emitted from the cavity.

By moving a mirror very far from laser material and the other mirror, on the order of kilometers, the laser cavity thus formed will have no out-cavity emissions (Linford et al, 1974). Lasing will occur only within the cavity when the alignment is correct.

Such a cavity is detectable only as an observer moves between the mirrors, and the lasing stops once the observer blocks the beam path. Such a laser would obviously be LPD (angle-limited), but questions remain as to whether the cavity can be aligned in a practical amount of time. If the link requires hours to acquire, then it is obviously impractical. The acquisition of a laser material with sufficient gain, yet practical to use in the field, will also determine practicality.

3.3 SUMMARY

The left-hand box of figure 1 summarizes all the efforts described above, both inhouse and contractual, carried out in the course of the ISRC project.

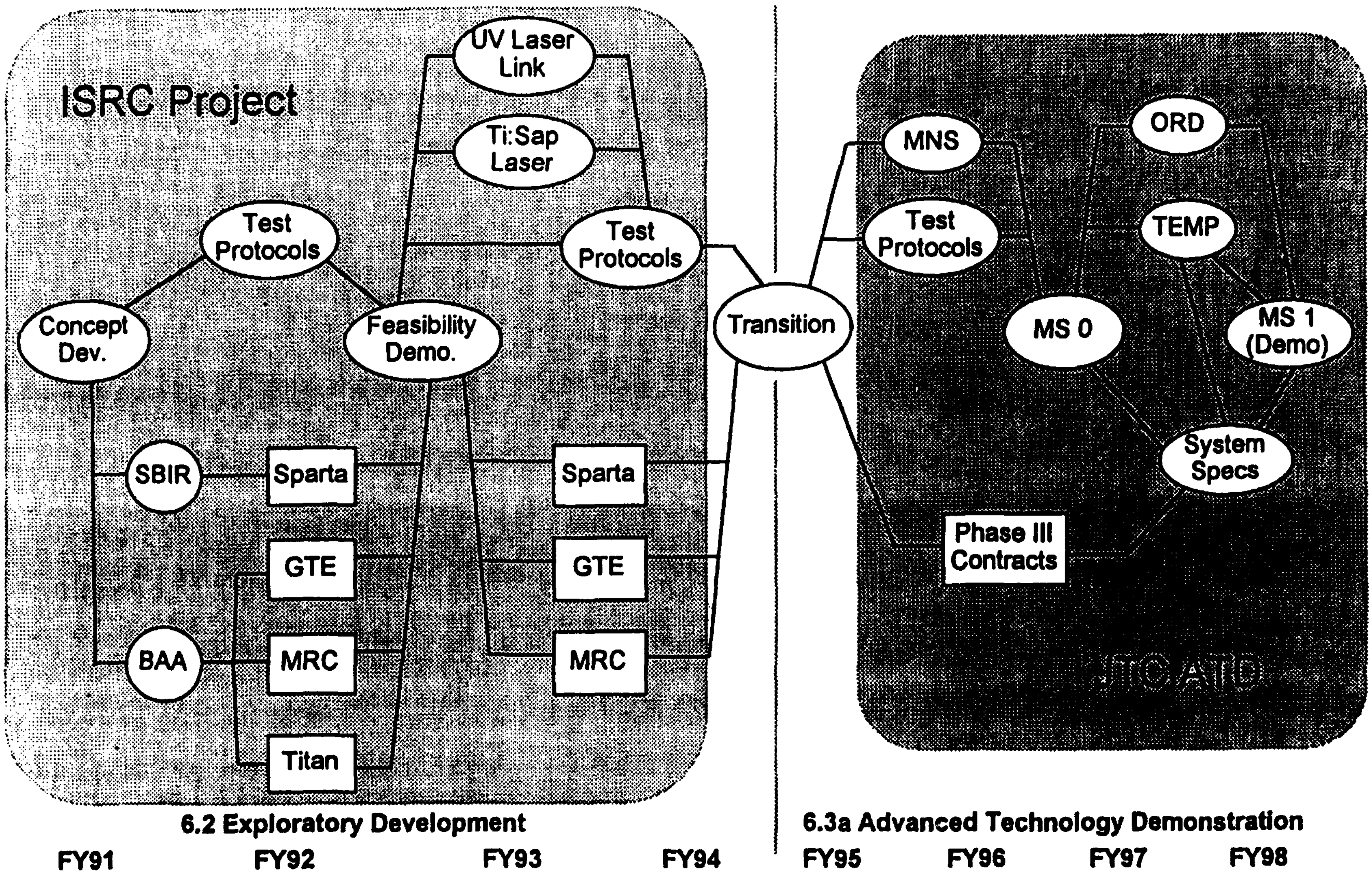

Figure 1. ISRC project road map.

4.0 PROGRESS SUMMARY

Work accomplished in FY 1993 and work to be continued in FY 1994 are described below.

4.1 NRaD INHOUSE

Test protocols were updated for the various ISRC links to support testing of the prototype links built by NRaD and its contractors (see appendix A). Testing of NRaD prototype links was performed to confirm test protocols and support testing of the prototype links built by the ISRC contractors.

Upon completion of the Ti:Sapphire laser cavity effort, a professional paper covering the work was submitted and published in the 15 November 1993 issue of Optics Letters (see appendix B).

4.2 CONTRACTS

The Small Business Innovation Research (SBIR) (Sparta) and the three Broad Agency Announcement (BAA) (GTE, MRC, and Titan) Phase I contracts awarded in FY 1992 were completed in November 1992. The Phase I results were evaluated and the Phase II recommendations presented to MARCORSYSCOM.

After consideration of the NRaD recommendations and the available funding, the sponsor selected three contractors (GTE, MRC, and Sparta) for the follow-on Phase II contracts. These Phase II contracts were awarded in May 1993.

These contracts are being monitored and are expected to be completed in May 1994. Summaries of these contracts to date are in appendices C through F.

4.3 FY 1994 EFFORTS

Develop plans for transitioning from the 6.2 ISRC exploratory development effort to a 6.3a advanced development effort.

Continue to upgrade test protocols for the various ISRC links as more technical information becomes available. Initiate development of Phase III test protocols.

Monitor the three Phase II contracts to completion, evaluate the results, and make recommendation for Phase III awards.

5.0 TRANSITION PLANS

The current ISRC 6.2 exploratory development effort is expected to be completed in FY 1994 (see table 1) and transition into a 6.3a Advanced Technology Demonstration (ATD) in FY 1995 (see figure 1).

Table 1. 6.2 exploratory development milestones.

Milestone Description	FY 94 Execution Year (Quarters)	FY 95 Budget Year (Quarters)
	1 2 3 4	1 3 4
a. Intentionally Short-Range Communications		
1. Complete analyses, design, and feasibility testing of Company Radio.	R H DRCT	(PE 63640M)
2. Complete analyses, design, and feasibility testing of LAN Backbone.	R H DRCT	(PE 63640M)
3. Complete analyses, design, and feasibility testing of Wideband Data Link.	R H DRCT	(PE 63640M)

C = Completion D = Demonstration H = Hardware R = Report T = Transition

Program Element 63640M is the Joint Tactical Communications (JTC) ATD.

5.1 JOINT TACTICAL COMMUNICATIONS (JTC) ATD

The Joint Tactical Communications (JTC) ATD is a Marine Corps 6.3a technology demonstration program to integrate various communications technologies into an overall tactical communications package that will serve the USMC into the next century.

Such technologies as wireless LPD/LPI provide security, mobility, and survivability to Marine Corps tactical units. Extensions of LPD/LPI communications to OTH ranges will enhance coordination within a MAGTF.

Table 2 shows how the ISRC project fits into the overall JTC ATD.

Table 2. Overall transition plan milestones.

Milestone Description	FY 92	FY 93	FY 94	FY 95	FY 96	FY 97	FY 98
6.2 Exploratory Development	——	——	——>				
6.3a Advanced Technology Demonstration (ATD)				<——	——	——	——>
Mission Need Statement					◊		
Milestone 0 (MS 0)					◊		
Concept Engineering (CE)						<——	——>
Ordinance Requirements Document (ORD)							◊
Test and Evaluation Master Plan (TEMP)							◊
MS 1							◊

5.2 ISRC MISSIONS TRANSITION PLAN

5.2.1 Transition Plan for Company Radio

The best options for the Company Radio voice link seem to be omnidirectional UV or DSSS that permeates a small area.

5.2.1.1 UV. A pulsed UV laser would provide a noise suppression advantage. Omnidirectional arc lamps should also be applied to the voice link. The use of broadband lamps will provide least expensive demonstration system, but may be problematical when multichannel aspects are to be considered. The development of a UV laser or lamp system, with its associated electronics and optics, can satisfy the requirements of the Company Radio.

5.2.1.2 DSSS. An omnidirectional DSSS link (to take advantage of its LPD and potential multi-path integration characteristics) should be developed to satisfy the Company Radio requirements.

5.2.1.3 MMW. The Army Communications and Electronics Command's (CECOM) EHF applique should be available for testing in FY 94.

5.2.1.4 IR. IR systems cannot satisfy NLOS and should not be considered.

5.2.2 Transition Plan for LAN Backbone, Low-Data-Rate

The best options for the low-data-rate LAN Backbone link are directional UV or DSSS that will cover a small arc and relieve the need to precisely aim the transceiver.

5.2.2.1 UV. A pulsed UV laser would provide a noise suppression advantage. Directional arc lamps may be usable for the low-data-rate links.

5.2.2.2 DSSS. A directional DSSS data link should be developed to take advantage of its LPD and high-data-rate characteristics.

5.2.2.3 MMW. The USA CECOM's EHF Wireless LAN prototype should be available for testing during FY 94.

5.2.2.4 IR. A directional IR laser diode link should be seriously considered for the low-data- rate LAN Backbone.

5.2.3 Transition Plan for LAN Backbone, High-Data-Rate

The best options for the high-data-rate LAN Backbone link seem to be the LOS DSSS, IR, or MMW that will cover a small arc. The system should be aimed with some precision.

5.2.3.1 DSSS. A directional DSSS LAN Backbone prototype should be developed to take advantage of its LPD and high-data-rate characteristics.

5.2.3.2 MMW. The USA CECOM's EHF Wireless LAN prototype should be available for testing during FY 94.

5.2.3.3 IR. A directional IR laser diode link is a viable alternative for the high-data-rate LAN Backbone and should be developed.

5.2.3.4 UV. An UV laser will not likely satisfy the high-data-rate requirement and should not be pursued at this time. UV lamps cannot achieve the necessary data rates at the required ranges and should not be considered.

5.2.4 Transition Plan for Wideband Data Link

The best options for the Wideband Data Link seem to be LOS DSSS, IR, or MMW, all of which will cover a small arc. The system can be aimed with precision.

5.2.4.1 DSSS. A directional DSSS Wideband Data Link prototype should be developed to take advantage of its LPD and high-data-rate characteristics.

5.2.4.2 MMW. Adapting the USA CECOM's EHF Wireless LAN prototype to satisfy the requirements of the Wideband Data Link may be possible. The prototype should be available for testing during FY 94.

5.2.4.3 IR. A directional IR laser diode link is a viable alternative for the Wideband Data Link and should be considered.

5.2.4.4 UV. An UV laser will not likely satisfy the high-data-rate requirement and should not be pursued at this time. UV lamps cannot achieve the necessary data rates at the required ranges and should not be considered.

5.3 RELATIONSHIP TO OTHER PROGRAMS

Figure 2 shows how other activities with similar interests, described below, will fit into the JTC ATD plan.

5.3.1 Army

USA CECOM, Fort Monmouth, New Jersey, has funded several efforts to develop tactical LPD, short-range communications systems where the range is limited by absorption of MMW in the atmosphere. CECOM has concentrated its efforts in EHF (or MMW) systems that use the absorption properties of EHF radiation in the atmosphere in order to limit detection range. CECOM funded the Hughes EHF Appliques, which operate at 54 GHz (5.6 mm) in the FM mode for a maximum ideal operational range of about 4 km and detection range of about 8 km, and are expected to be delivered in the first quarter of FY 94. CECOM is also funding Rockwell and Chang Industries to develop LPD Wireless LAN systems based on EHF radiation. The Rockwell system uses 36-GHz EHF, while the Chang system uses 54 GHz. Prototype units were delivered to the Army in 1993 and were demonstrated during STDN-4.

MARCORSYSCOM has partially funded CECOM to leverage these candidate ISRC systems for Marine Corps applications. The test protocols developed by NRaD under ISRC program will be used to evaluate CECOM's EHF communication systems.

5.3.2 Air Force

USAF Wright Laboratory, Dayton, Ohio, has funded several efforts to develop tactical LPD, short-range communications systems for communications between airframes. These efforts involved solar-blind UV and spread spectrum technologies.

5.3.3 Other Activities

Other activities such as SOCOM and DEA have similar requirements for short-range LPD/LPI communications systems.

5.4 RISK ASSESSMENT

The risk assessment will be based upon how well the candidate ISRC systems perform when tested with the refined ISRC test protocols during FY 1994.

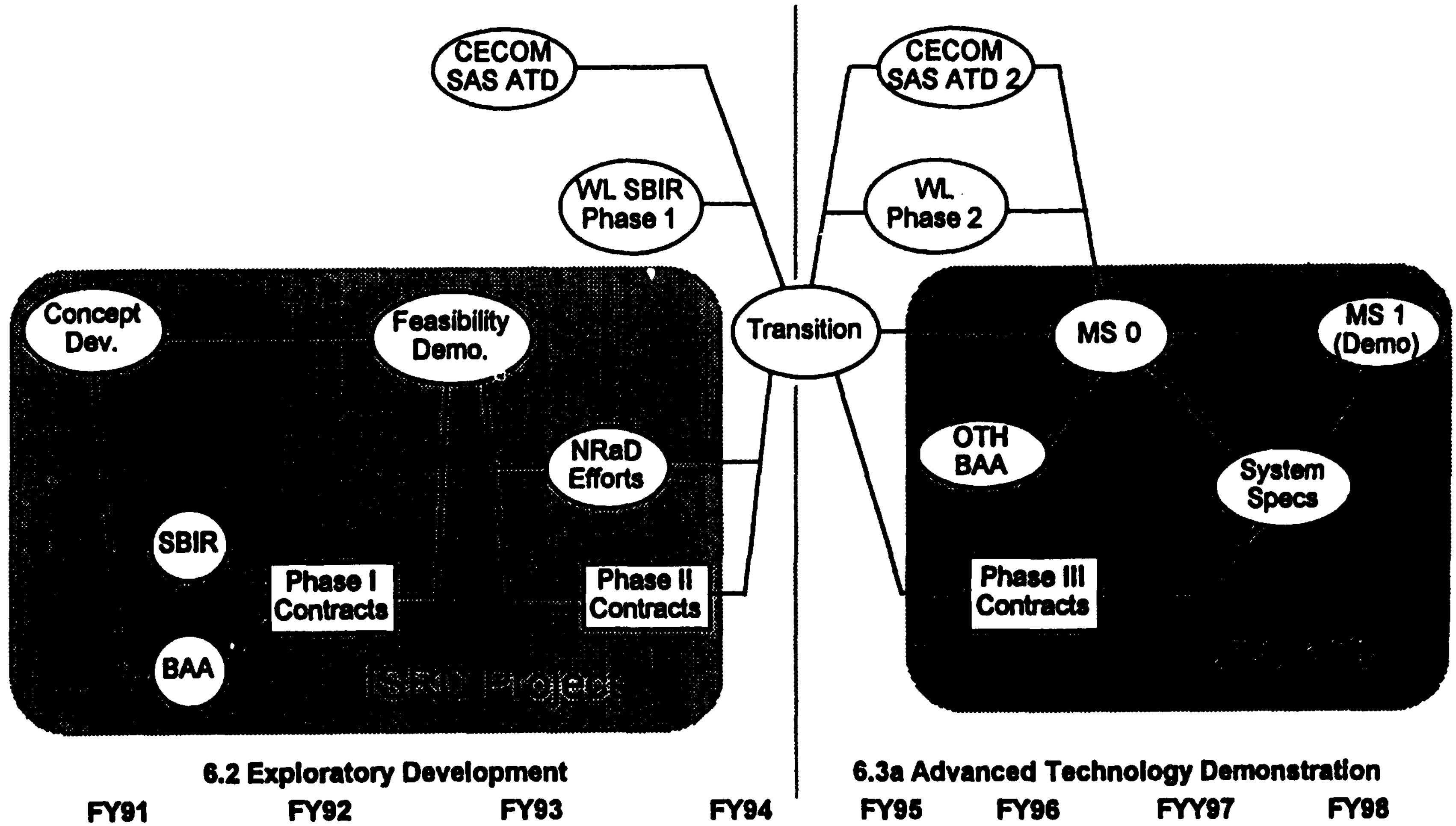

Figure 2. JTC ATD road map.

6.0 RECOMMENDATIONS

6.1 TRANSITION

Complete plans for transitioning the ISRC 6.2 exploratory development effort into the 6.3a JTC ATD.

6.2 TEST PROTOCOLS

Continue to refine the test protocols for all of the ISRC technologies in anticipation of folding them into the JTC Test and Evaluation Master Plan (TEMP).

6.3 CONTRACTS

Evaluate the results of the ISRC Phase II contracts and recommend candidate technologies for continued development during Phase III and JTC ATD.

6.4 AMPHIBIOUS OPERATIONS

Apply the technologies developed for ISRC missions to covert and amphibious missions. Determine the feasibility of extending the range of systems developed for ISRC to satisfy OTH requirements.

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8.0 GLOSSARY

ATD	Advanced Technology Demonstration
BAA	Broad Agency Announcement
BER	bit error rate
Broadband	a broad spectrum of wavelengths
CAINS	Carrier Aircraft Inertial Navigation System
CBD	Commerce Business Daily
CECOM	USA Communications Electronics Command
CP	command post
Directional	direction is within ±5 deg of the imaginary line between terminals
DRT	diagnostics rhyme test
DSSS	direct sequence spread spectrum
Duplex	two-way channel
EHF	extremely high frequency, see MMW
IR	infrared light, $\lambda > 700$ nm
ISRC	Intentionally Short-Range Communications
JTC	Joint Tactical Communications
LAN	local-area network
LOS	line-of-sight, direction within ±1 deg of the imaginary line between terminals
LPD/LPI	low probability of detection/intercept
MAGTF	Marine Air-Ground Task Force
MARCORSYSCOM	Marine Corps Systems Command, Quantico, Virginia
MMW	millimeter wave, with $1 \text{ mm} \le \lambda \le 10 \text{ mm}$, or $30 \text{ GHz} \le \nu \le 300 \text{ GHz}$ (see EHF)
NCCOSC	Naval Command, Control and Ocean Surveillance Center, San Diego, California
Nd:YAG	neodymium-doped yttrium aluminum garnet crystal
NLOS	non-line-of-sight, or no LOS between the transmitter and the receiver
NRaD	NCCOSC Research, Development, Test and Evaluation (RDT&E) Division (formerly Naval Ocean Systems Center), San Diego, California

Omnidirectional	the signal is sent in all directions azimuthally
OTH	over-the-horizon
PMT	photomultiplier tube
PPM	pulse position modulation
RF	radio frequency
SBIR	Small Business Innovation Research
SHF	super high frequency
Simplex	one-way channel
USMC	United States Marine Corps
UV	ultraviolet light, 200 nm $\leq \lambda \leq$ 400 nm
WAN	wide area network
Wideband	a wide range of data rates

APPENDIX A. ISRC TEST PROTOCOLS

1.0 INTRODUCTION

This appendix provides a single set of test protocols, or test requirements and procedures, that the Intentionally Short-Range Communications (ISRC) links will have to satisfy. This appendix updates the test protocols that appeared originally in appendix A of NRaD TD 2286 and revised in appendix A of NRaD TR 1600.

The test protocols currently include some quantified test requirements; the test procedures will be further developed through Fiscal Year 1994. The Phase II contractors will be given the opportunity to comment on these requirements before incorporating them into their Phase II test plans.

The test protocols will be continuously refined (in future publications) as more technical information becomes available, eventually to be folded into the Joint Tactical Communications (JTC) Test and Evaluation Master Plan (TEMP).

2.0 GENERAL REQUIREMENTS

The following ISRC general requirements apply to each ISRC link, although the quantitative requirements for these parameters are link specific.

2.1 LPD

Low probability of detection (LPD) is defined here to mean that the enemy has a low likelihood to detect and perform direction finding on our transmissions. A system that cannot be detected is inherently low probability of intercept (LPI).

An LPD link with an operational range of X km must have a detection range of less than X+Y km.

The operational ranges of the ISRC links vary from 0.5 km to 5 km (0.5 km $\leq$ X $\leq$ 5 km). In general, an ISRC link must have a detection range of less than 5 to 7 km (X $\leq$ X+Y $\leq$ 7 km), preferably less.

2.2 NLOS

The non-line-of-sight (NLOS) characteristic is highly desirable because tactical operations tend to involve situations where obstructions to line-of-sight are abundant.

NLOS means that no single unobstructed line exists between the transmitter and the receiver (i.e., a structure lies between them). If complete NLOS is not achievable for a particular link, a partial requirement is that the link is viable when there is a misalignment of at least a minimum angle (i.e., such as 5 degrees).

2.3 TEMPERATURE

ISRC links must operate in temperatures ranging from 0 to 50 degrees C.

2.4 SIZE AND WEIGHT

The final (Phase III) communications system must be rugged and mobile in order to be mounted on a high-mobility multipurpose wheeled vehicle (HMMV) or similar Marine Corps

vehicle. Therefore, the total weight of the system shall not exceed 100 kg and the total volume shall not exceed 1 m^3.

2.5 POWER

The final (Phase III) communications system shall function on HMMV power (100 A at 27 VDC).

3.0 LOW-DATA-RATE LINKS REQUIREMENTS

In general, the Company Radio and the low-data-rate LAN Backbone need to satisfy the same general requirements because of the similarities of data rate and operational configurations. The differences include the range, data format, and operational methods.

3.1 COMPANY RADIO

The Company Radio is characterized by very-short-range ($\leq$ 0.5 km), omnidirectionality, low-data-rate, and mobility.

3.1.1 BER

The Company Radio is distinguished by a voice link that will then tolerate a large bit error rate (BER). Uncorrected BER for a reasonable voice system is $\leq 10^{-2}$.

3.1.2 Data Rate

An adequate digital voice system will need at least 2400 bps link throughput. The diagnostic rhyme test (DRT) rating for this voice link shall be $\geq$ 0.90 for good quality voice.

3.1.3 Omnidirectionality

The Company Radio needs to operate in an omnidirectional mode. The operator need not orient the system in order to communicate, since the positions of other terminals may be moving or unknown.

However, under conditions when some knowledge of another terminal's position is available, some aiming to improve link connection (and reduce detectability) can be an useful additional asset.

The Company Radio must be capable of omnidirectionality, but be allowed to operate directionally when circumstances permit.

Multiple transceivers may be necessary to achieve omnidirectionality for some technologies.

3.2 LAN BACKBONE

The low-data-rate LAN Backbone is a short-range ($\leq$ 1.0 km), semidirectional, transportable, data link.

3.2.1 BER

The uncorrected BER requirement for this link shall be $\leq 10^{-4}$. Error correction procedures shall be implemented to reduce corrected BER to $\leq 10^{-6}$.

3.2.2 Data Rate

The minimal data rate required to connect a server computer to a terminal computer will be 2400 bps. However, higher data rates (such as 4800 bps, 9600 bps or 14.4 kbps) will be a plus factor in evaluating the link.

3.2.3 Directionality

The low-data-rate LAN Backbone needs to operate in a directional mode in several different directions, although one at a time. The operator need not orient the system very precisely to communicate because the link can sustain an angular misalignment of at least 5 degrees. However, more precise aiming to improve link would be considered an additional asset if it improves link performance.

3.2.4 LAN Software

Until a specific LAN operating system (such as MTS) is defined for the USMC, the Banyan VINES LAN software will be used to operate the LAN Backbone.

4.0 HIGH-DATA-RATE LINKS REQUIREMENTS

In general, the Wideband Digital Data Link and the high-data-rate LAN (or WAN) Backbone need to satisfy the same general requirements because of the similarities of data rate and operational configurations. The differences include the range, data format, and operational methods.

4.1 LOS

These links can be directional because they are stationary when in operation and the positions of other terminals should be known. However, that may represent additional problems in acquisition (between moves). The high-data-rate links shall be operated in a LOS mode in several different directions, although only one direction at a time.

4.1.1 Misalignment

By sustaining an angular misalignment of at least 1 degree, the system develops the capability to operate without very precise alignment. Link connectivity, despite misalignment, will be a valuable asset in terms of operational simplicity and personnel effectiveness. More precise aiming to improve link would be considered an additional asset if it improves link performance.

4.2 WIDEBAND DATA LINK

The Wideband Data Link is a medium-range (3 to 5 km), directional, vehicle-mounted or fixed, high-data-rate, digital data link.

4.2.1 BER

The uncorrected BER requirement shall be $\leq 10^{-5}$. Error correction procedures shall be implemented to reduce corrected BER to $\leq 10^{-7}$.

4.2.2 Data Rate

The data link will require a minimum throughput of 1.6 Mbps (T1) to replace the land lines connecting the command post to an antenna farm.

4.3 LAN/WAN BACKBONE

The high-data-rate LAN/WAN Backbone is a short-range ($\leq$ 1.0 km), semidirectional, transportable, data link.

4.3.1 BER

The uncorrected BER requirement shall be $\leq 10^{-5}$. Error correction procedures shall be implemented to reduce corrected BER to $\leq 10^{-7}$.

4.3.2 Data Rate

The link will require a minimum throughput of 1.6 Mbps (T1) to provide connectivity between a server computer and either a terminal computer or another server computer.

4.3.3 Software

Until a specific LAN operating system (such as MST) is defined for the USMC, the Banyan VINES LAN software will be used to operate the LAN/WAN Backbone.

5.0 ENVIRONMENTAL REQUIREMENTS

Various environmental factors affect the ISRC links. However, because each link (and technology) is different, the impact of different environmental factors varies. The following are some factors impacting upon the ISRC links.

5.1 OZONE

An ISRC link based on UV radiation is expected to operate in an urban environment; that is, the ozone concentration is between 30 to 100 ppb (Yen, 1987). A nominal ozone level of 50 ppb is to be expected in a test.

5.2 FOG

An ISRC link should be able to operate in thin fog (defined here as a visibility of 1 km). The definition of "thin fog" is imprecise because fog density depends on particulate density and size.

5.3 RAIN

An ISRC link should be able to operate in moderate rain (defined here as a rain rate of 1 inch/hour).

5.4 NOISE SOURCES

An ISRC UV link is expected to operate during daylight in the presence of noise sources such as arc-welding, flames, and explosions (at the same distance from the receiver as the transmitter). Specific sources will be listed in section 6.

An ISRC MMW or DSSS link is expected to operate during daytime in the presence of RF sources (at the same distance from the receiver as the transmitter) likely to exist in a battlefield. Specific sources will be stated in section 6.

An ISRC IR link is expected to operate during daylight in the presence of noise sources such as flames and explosions (at the same distance from the receiver as the transmitter).

5.5 FOLIAGE

The low-data-rate ISRC links are expected to operate in spite of foliage between the transmitter and the receiver. Precise characteristics will be defined in conjunction with the contractors and Marine Corps personnel.

5.6 OBSTRUCTIONS

The low-data-rate ISRC links are expected to operate in the presence of obstructions such as buildings that block the line-of-sight. More precise specifications for each prototype link shall be defined in conjunction with the contractors.

6.0 PHASE II TEST REQUIREMENTS

Since the various ISRC Phase II prototype links employ different technologies, it is impractical to apply one set of test criteria for all links. Each link has its own strengths and weaknesses that should be tested. Therefore, requirements will be delineated for each prototype link.

Each Phase II link shall be a one-way link transmitting actual data. The specific test procedures corresponding to each of the ISRC links have been developed during FY 1993 and 1994. In addition to satisfying the specific mission requirements, an ISRC link must satisfy the system and environmental requirements listed in sections 2 through 5 of this appendix.

The initial draft of the complete test protocols shall be distributed to the three Phase II contractors. The contractors will be invited to participate in refining these test protocols and then incorporate these revised test protocols into their Phase II test plans.

6.1 MRC UV LASER LINK

The Mission Research Corporation (MRC) one-way brassboard is based on a UV laser. The primary mission the system seeks to satisfy is the low-data-rate LAN Backbone, and the operational ranges tested shall be 0.5, 0.75, and 1.0 km.

6.1.1 NLOS

Link connectivity shall be demonstrated with a building between the transmitter and the receiver such that no direct path between them exists.

6.1.2 Directionality

MRC shall determine the maximum off–boresight angle at which the receiver can acquire an acceptable signal at the test ranges.

6.1.3 Data Rate

Transfer over the air of actual data at a rate of 4.8 kbps shall be demonstrated.

6.1.4 BER

MRC shall perform sufficient data transfer to compute link BER. Transfer of large files and subsequent file comparison will satisfy this requirement.

6.1.5 LPD/LPI

MRC shall determine the maximum detection range when the link is operating at the test ranges. Use of current receiver to direction find is acceptable.

6.1.6 Noise

MRC shall introduce noise source(s) while the link is operating at the test ranges and quantify degradation effects on the link. SNR shall be computed for each noise source.

6.1.7 Ozone

MRC shall quantify the effect of ozone concentration on link performance.

6.1.8 Environmental Factors

MRC shall determine the effect of environmental factors on link performance when such conditions occur at the test site.

6.2 SPARTA UV LAMP LINK

The Sparta one-way brassboard is based on a UV surface discharge. The primary mission the system seeks to satisfy is the Company Radio, and the operational ranges tested shall be 0.5 and 0.75 km.

6.2.1 NLOS

Link connectivity shall be demonstrated with a building between the transmitter and the receiver such that no direct path between them exists.

6.2.2 Directionality

Sparta shall determine the maximum off-boresight angle at which the receiver can acquire an acceptable signal at the test ranges.

6.2.3 Connectivity

Transfer over the air of voice at an effective rate of 2.4 kbps shall be demonstrated.

6.2.4 BER

Sparta shall attempt to quantify BER for the demonstration link.

6.2.5 LPD/LPI

Sparta shall determine the maximum detection range when the link is operating at the test ranges. Use of current receiver to direction find is acceptable.

6.2.6 Noise

Sparta shall introduce noise source(s) while the link is operating at the test ranges and quantify degradation effects on the link. SNR shall be computed for each noise source.

6.2.7 Ozone

Sparta shall quantify the effect of ozone concentration on link performance.

6.2.8 Environmental Factors

Sparta shall determine the effect of environmental factors on link performance when such conditions occur at the test site.

6.3 GTE DSSS LINK

The GTE one-way brassboard is based on DSSS technology. The primary mission the system seeks to satisfy is the low-data-rate LAN Backbone, and the operational ranges tested shall be 0.5, 0.75, and 1.0 km.

6.3.1 NLOS

Link connectivity shall be demonstrated with a building between the transmitter and the receiver such that no direct path between them exists.

6.3.2 Directionality

GTE shall determine the maximum off-boresight angle at which the receiver can acquire an acceptable signal at the test ranges.

6.3.3 Data Rate

Transfer over the air of real data at a data rate of at least 16 kbps shall be demonstrated.

6.3.4 BER

GTE shall perform sufficient data transfer to compute link BER. Transfer of large files and subsequent file comparison will satisfy this requirement.

6.3.5 LPD/LPI

GTE shall determine the maximum detection range when the link is operating at the test ranges. Use of current receiver, spectrum analyzer, or radiometer to direction find is acceptable.

6.3.6 Noise

GTE shall introduce noise source(s) while the link is operating at the test ranges and quantify degradation effects on the link. SNR shall be computed for each noise source.

6.3.7 Environmental Factors

GTE shall determine the effect of environmental factors on link performance when such conditions occur at the test site.

6.4 GENERIC MMW LINK

A MMW/EHF system that seeks to satisfy the low-data-rate LAN Backbone shall be tested at operational ranges of 0.5, 0.75, and 1.0 km.

6.4.1 NLOS

Link connectivity shall be demonstrated with a building between the transmitter and the receiver such that no direct path between them exists.

6.4.2 Directionality

The maximum off–boresight angle at which the receiver can acquire an acceptable signal at the test ranges shall be determined.

6.4.3 Data Rate

Transfer over the air of real data at a data rate of at least 2.4 kbps shall be demonstrated.

6.4.4 BER

Sufficient data transfer to compute link BER shall be performed. Transfer of large files and subsequent file comparison will satisfy this requirement.

6.4.5 LPD/LPI

The maximum detection range when the link is operating at the test ranges shall be determined. Use of current receiver to direction find is acceptable.

6.4.6 Noise

Noise source(s) shall be introduced while the link is operating at the test ranges and the degradation effects on the link quantified. SNR shall be computed for each noise source.

6.4.7 Environmental Factors

The effect of environmental factors on link performance shall be determined when such conditions occur at the test site.

6.5 GENERIC IR LINK

An IR system that seeks to satisfy the low-data-rate LAN Backbone shall be tested at operational ranges of 0.5, 0.75, and 1.0 km.

6.5.1 NLOS

Link connectivity shall be demonstrated with a building between the transmitter and the receiver such that no direct path between them exists.

6.5.2 Directionality

The maximum off-boresight angle at which the receiver can acquire an acceptable signal at the test ranges shall be determined.

6.5.3 Data Rate

Transfer over the air of real data at a data rate of at least 2.4 kbps shall be demonstrated.

6.5.4 BER

Sufficient data transfer to compute link BER shall be performed. Transfer of large files and subsequent file comparison will satisfy this requirement.

6.5.5 LPD/LPI

The maximum detection range when the link is operating at the test ranges shall be determined. Use of current receiver to direction find is acceptable.

6.5.6 Noise

Noise source(s) shall be introduced while the link is operating at the test ranges and the degradation effects on the link quantified. SNR shall be computed for each noise source.

6.5.7 Humidity

The effect of humidity on link performance shall be determined.

6.5.8 Environmental Factors

The effect of environmental factors on link performance shall be determined when such conditions occur at the test site.

7.0 PHASE III REQUIREMENTS

The Phase III prototype link shall be a two-way link that transfers actual data outside the laboratory environment. Since the Phase III requirements will largely depend on Phase II results, only an outline will be given at this stage to initiate the development. These requirements will eventually be integrated into the JTC TEMP.

7.1 MULTICHANNEL

The Phase III link must be able to communicate even when the two terminals transmit simultaneously. Ideally, at least two distinct channels will be provided to the link, so that the link will be assured of connectivity even in the event of simultaneous transmissions. Some link protocol will then determine which of the simultaneous transmissions will have priority.

7.1.1 UV Laser Link

A UV laser that can be tuned to several wavelengths is the ideal solution to the multichannel requirement. Filters that can discriminate between these wavelengths will also be required.

7.1.2 UV Lamp Link

A set of UV lamps, emitting at several wavelengths, will satisfy the multichannel requirement. Optical filters that can discriminate between these wavelengths will also be required.

7.1.3 MMW Link

A set of distinct-frequency MMW/EHF antennas will satisfy the multichannel requirement.

7.1.4 IR Link

A laser that can be tuned to several wavelengths will solve the multichannel requirement. Filters that can discriminate between these wavelengths will be required.

7.1.5 DSSS Link

A set of distinct-frequency antennas or two orthogonal spread spectrum modems will satisfy the multichannel requirement. Power control becomes an issue if a single transceiver at each terminal is used.

7.2 RUGGEDIZATION

The Phase III hardware must be suitable for testing under field conditions by scientific or technical personnel.

7.3 SIZE/WEIGHT

The size and weight must be minimized to be practical under the mobility constraints of the maneuver warfare doctrine.

7.4 DATA RATE

The data rate must be maximized to handle the information transfer for the modern battlefield.

APPENDIX B. TI:SAPPHIRE PAPER

1.0 INTRODUCTION

During FY 1992–1993, NRaD Code 843 attempted to develop an intracavity-tripled titanium-doped sapphire (Ti:Al_2O_3) laser as a tunable ultraviolet (UV) emitter.

The goal of this effort was to provide the Intentionally Short-Range Communications (ISRC) project with a tunable UV laser source operating at 2500 pulses per second and UV power output substantial enough to be quantified.

Upon the completion of this experiment, a professional paper was submitted and published in the 15 November 1993 issue of Optics Letters (18,1925). The following is a reprint of the article.

2.0 PAPER AS PUBLISHED

Intracavity frequency doubling of a 2.5-kHz pulsed Ti:Al_2O_3 laser

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Received May 24, 1993

Efficient tunable deep-blue generation has been demonstrated from a 2.5-kHz Ti:Al_2O_3 laser through intracavity frequency doubling with β-BaB_2O_4. An output power of 170 mW at 397 nm was obtained with an efficiency of 7.4% from the pulse 532-nm pump source. The frequency-doubled output was tuned from 383 to 407 nm.

Titanium-doped sapphire (Ti:Al_2O_3) lasers have been demonstrated to be efficient lasers and a reliable alternative to dye lasers in the deep-red and near-infrared regions.[1,2] Combined with nonlinear conversion techniques they can be used as tunable sources in the blue and ultraviolet. Previous approaches for second-harmonic generation with Ti:Al_2O_3 laser have generally been based either on pulse pumping at relatively low repetition rates with moderate to high energy from frequency-doubled Nd:YAG lasers[3–5] or on cw pumping and mode-locked operation.[6,7] These approaches have been motivated by the desire to achieve either large pulse energies or extremely short pulse lengths. There are other applications, however, in which a tunable blue or ultraviolet output at intermediate repetition frequencies of a few kilohertz would be useful. Such sources could be modulated to permit voice communication. For example, blue-green sources are optimum for underwater communication. Also, the development of laser sources in the ultraviolet region from 260 to 280 nm is considered a promising approach for an intentionally short-range communication system through the atmosphere. Such systems are envisaged for a variety of military and civilian applications.[8] A tunable or multiwavelength source would also be desirable for multiple-channel or bidirectional operation.

In this research we have characterized an intracavity frequency-doubled Ti:Al_2O_3 laser, using a cw-pumped, repetitively Q-switched Nd:YAG laser as the pump source. This approach leads to an efficient, tunable blue source that could provide a reliable, all-solid-state system based on laser diode pumping.

The pump source for the Ti:Al_2O_3 laser was a Quantronix cw lamp-pumped, repetitively Q-switched Nd:YAG laser. The laser was intracavity frequency doubled to 532 nm and capable of 2.7 W of maximum average power at 2.5 kHz in a nearly TEM_{00} beam. A combination of a half-wave plate and a polarizer was used to vary the pump intensity incident upon the Ti:Al_2O_3 cavity. This allowed the Nd:YAG laser to operate at full power and preserved the pump beam's spatial and temporal characteristics. The pulse energy ranged up to 1.08 mJ, and each pulse had a FWHM of ~50 ns. The Ti:Al_2O_3 laser cavity is shown schematically in Fig. 1. The pump was focused with a 10-cm lens through the high-reflecting cavity mirror M1 and onto a 15-mm-long, Brewster-cut Ti:Al_2O_3 crystal that absorbed ~90% of the pump energy. A small fraction of the pump beam was reflected to a detector, which was calibrated to give the pump energy transmitted through the mirror and incident upon the Ti:Al_2O_3 crystal.

We made initial measurements of the laser performance at ~800 nm in order to optimize the cavity geometry and verify theoretical predictions of the pump threshold. We used two simple folded cavities similar to the one shown in Fig. 1 but without the nonlinear crystal and tuning plate. The results are shown in Fig. 2. Mirror M3 was a 30-cm-radius 0.6% transmissive output coupler in each case. For the first cavity, which gave the highest output and slope efficiency, mirrors M1 and M2 both had a 30-cm radius and the fold angle was 90 deg. The mirror separations were 16.5 cm (M1 to M2) and 14 cm. We observed a lower threshold with the second cavity, where M1 and M2 had a 5- and 10-cm radii, respectively, the mirror separations were 15 and 40 cm, and the fold angle was 40 deg. The laser is clearly able to operate well above threshold in either case, and a maximum efficiency of more than 5% was achieved. Since the pump pulse duration is much shorter than the $Ti:Al_2O_3$ fluorescence lifetime of ~3 μs and the repetition period is much longer, the threshold pump energy P_{th} depends only on the absorbed pump energy per pulse. When the pump

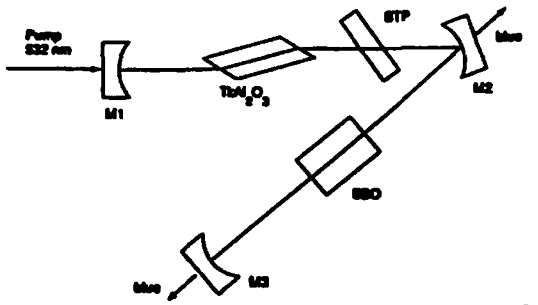

Fig. 1. Experimental layout for intracavity second-harmonic generation. BTP, quartz birefringent tuning plate; BBO, β-BaB_2O_4 crystal.

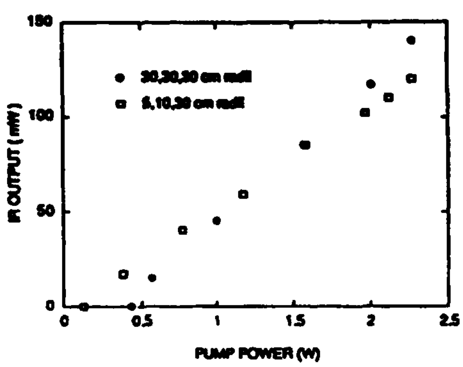

Fig. 2. Laser performance at the fundamental wavelength for two cavity geometries. The output coupling is $T = 0.6\%$.

and laser cavity modes are both TEM_{00}, the threshold is given by[9,10]

$$P_{th} = n\pi h\nu_p X(\omega^2 + \omega_p^2)/(4\sigma\eta_a). \qquad (1)$$

Here X is the total round-trip cavity loss including mirror transmission, $\langle\omega^2\rangle$ and $\langle\omega_p^2\rangle$ are the mean square cavity and pump mode radii, respectively, averaged over the pumped length of the crystal, $\sigma = 3 \times 10^{-19}$ cm^2 is the peak emission cross section at 800 nm, and η_a is the fraction of pump energy absorbed in the crystal. In this equation the refractive index $n = 1.76$ accounts for the elliptical distortion of the Gaussian beams inside the Brewster-cut laser crystal; however, the astigmatism that is due to the folded cavity has been neglected. The passive loss at 800 nm in the $Ti:Al_2O_3$ crystal that results from absorption and scatter was measured to be ~4% per pass, and the total round-trip cavity loss was estimated to be ~10%. The measured thresholds are somewhat higher than predicted. For the higher-threshold cavity (M1, M2, and M3 all with 30-cm radii), $\langle\omega^2\rangle$ is ~200^2 μm^2 with little astigmatism. We estimate the pump beam waist to be ~50 μm with this focusing geometry, which results in a calculated pump energy threshold of 76 μJ, or 0.19 W of average power incident upon the Ti:sapphire crystal. The observed threshold of ~0.4 W is reasonably consistent with this, considering the uncertainty in the pump beam area. A much lower threshold was obtained with the smaller-radius mirrors, for which the calculated mode radii were <100 μm and significantly astigmatic. The slope efficiency, however, was slightly lower owing to less efficient overlap and extraction of the pump beam with the smaller cavity modes.

Spectral measurements of the laser output were made with a spectrograph and silicon detector array. The output from the bare cavity was ~45 nm FWHM centered at 800 nm. With the addition of a 1-mm-thick crystal-quartz birefringent tuning plate to the cavity, we were able to tune the infrared output in a single band with a FWHM of ~3.5 nm over more than 50 nm. The calculated free spectral range of the 1-mm plate was more than 70 nm.

For the experiments with intracavity frequency doubling, all three mirrors were high reflecting at 800 nm with 10-cm radii of curvature. The fold angle was 40 deg, and the mirror spacings were ~15 cm. The selection of this configuration was based on the desire to obtain a small mode waist in both arms of the cavity. In this case, the calculated waist radii were ~110 μm with little astigmatism. Thus we would expect to find a pump threshold intermediate between the values observed in the two cases above. The choice of cavity geometry for optimizing the fundamental laser performance was found to be somewhat arbitrary since the primary consideration is the mode spot size at the $Ti:Al_2O_3$ crystal. However, we found that the frequency-doubling performance was improved with the above choice of mirrors, which also gave a small waist in the second arm.

A 5-mm-long β-BaB_2O_4 (BBO) crystal cut at 30 deg for type I doubling was placed at the waist position in the second arm of the cavity as shown in Fig. 1. The

BBO crystal was mounted in a sealed cell containing deuterated Decalin index-matching fluid. Both cell windows were antireflection coated for 800 and 400 nm. The 1-mm quartz plate was placed in the cavity to permit tuning and to reduce the linewidth at the fundamental wavelength. By adjusting both the tuning plate and the BBO phase-matching angle, we were able to tune the second-harmonic output over 25 nm from 383 to 408 nm as shown in Fig. 3 for ~1 W of pump power. With higher pump power and different tuning plates, it would be possible to tune over a much larger range. Nonlinear conversion occurs in both directions in this arm of the cavity, and blue light was observed from both mirrors M2 and M3 with comparable intensity. The blue powers given here and below represent the total output exiting both mirrors. A small amount of leakage at the fundamental wavelength was also observed and accounted for. It would probably have been useful to have mirror M3 also coated to reflect the blue so that both outputs would be combined and exit from M2. In fact, the nonlinear interaction length can be increased, and enhanced conversion is possible if the correct phase between the fundamental and second harmonic can be maintained for the second pass through the nonlinear crystal.[11]

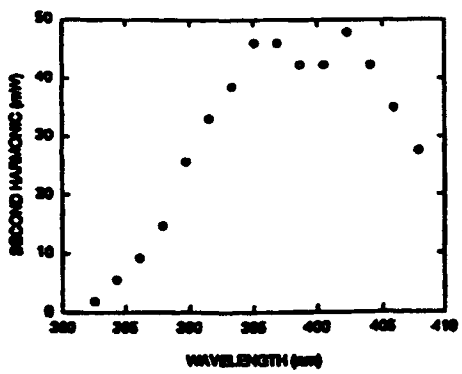

Fig. 3. Tuning curve for second-harmonic generation with ~1 W of pump power.

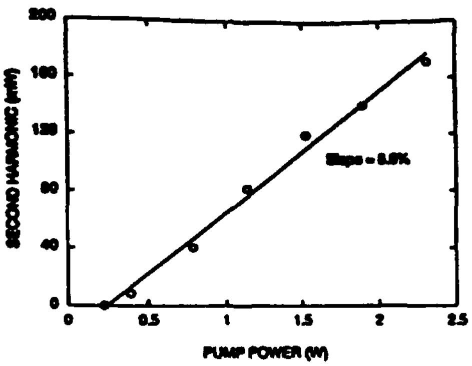

Fig. 4. Second-harmonic output power at 397 nm.

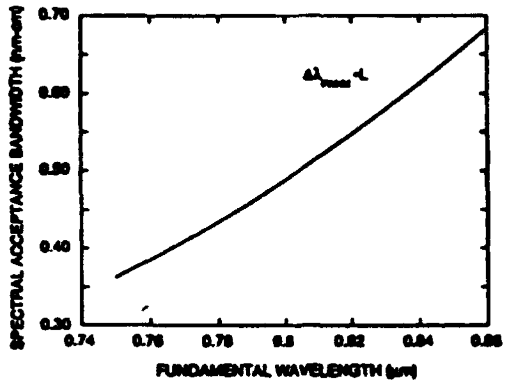

Fig. 5. Calculated spectral acceptance bandwidth (FWHM) at the fundamental wavelength for frequency doubling in BBO.

The total frequency-doubled output at 397 nm with pump power is plotted in Fig. 4. The pump threshold in this case was ~250 mW, which indicates that the cavity loss was low. We obtained 170 mW of second-harmonic power (68 μJ/pulse) at 7.4% total efficiency and 8.5% slope efficiency from the 532-nm pump. At maximum pump power, the second-harmonic spectrum had a FWHM of ~1.4 nm, corresponding to 2.8 nm at the fundamental. The spectral acceptance bandwidth (FWHM) for type I frequency doubling in BBO ($oo \rightarrow e$) is given by

$$\Delta\lambda = 2.7832\lambda_1/[\pi L(2dn_{o1}/d\lambda_1 - dn_{e2}/d\lambda_2)], \quad (2)$$

where n_{o1} and n_{e2} are the ordinary and extraordinary refractive indices at the fundamental and second-harmonic wavelengths, respectively.[12] This function is plotted in Fig. 5. At $\lambda_1 = 800$ nm, the acceptance bandwidth is 0.98 nm for our 5-mm-long crystal. This indicates that the second-harmonic generation efficiency could be improved by a reduction in the laser linewidth, which is generally achieved by the addition of additional thicker plates to the birefringent tuning plate stack.[13] It is surprising that we observed reasonably good conversion efficiency over a fundamental bandwidth approximately 2.5 times the spectral acceptance bandwidth. The probable explanation for this is the very sensitive phase-matched wavelength tuning with angle—approximately 1.6 nm/mrad at 800 nm. Calculations show that the divergence of the TEM_{00} mode near the secondary waist in our cavity is large enough to account for the additional bandwidth.

We did observe some apparent thermal problems with the fluid-filled BBO cell when we were frequency doubling at higher average power. This was probably due to a small absorption from vibrational overtones of the deuterated Decalin.[14] After a period of several seconds, the blue output became unstable, with fluctuations in spatial profile and total intensity.

In summary, we have demonstrated efficient deep-blue generation from an intracavity frequency-doubled $Ti:Al_2O_3$ laser at a 2.5-kHz repetition rate. At 397 nm, the maximum conversion was 7.4% from the 532-nm pump. This is somewhat better than has been reported for mode-locked $Ti:Al_2O_3$ lasers with either intracavity[7] or external[6] frequency doubling. However, with significantly larger pump pulse energy at 532 nm, greater than 20% conversion to the blue has been reported[5,15] with external doubling of the collimated fundamental beam.

We thank the U.S. Marine Corps Systems Command for supporting this research and Milan Kokta of Union Carbide for providing the $Ti:Al_2O_3$ crystal.

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APPENDIX C. GTE CONTRACT OVERVIEW

1.0 BACKGROUND

The Intentionally Short-Range Communications (ISRC) project solicited through the Broad Agency Announcements (BAA) for technologies that can provide low probability of detection and intercept (LPD/LPI) tactical communications.

Three contracts were awarded under the BAA solicitation N66001-92-X-6005. This appendix summarizes one BAA Phase I contract effort and the Phase II follow-on effort to date.

1.1 OBJECTIVE

1.1.1 Phase I

The GTE Government Systems Corporation in Waltham, Massachusetts, proposed to develop a short-range, LPD, tactical communications system based on direct sequence spread spectrum (DSSS) techniques that satisfy the ISRC requirements.

A report based on the results of a vulnerability analysis study and a field demonstration plan for Phase II were delivered at the conclusion of Phase I.

1.1.2 Phase II

The feasibility of the proposed one-way breadboard link developed during Phase I shall be demonstrated by GTE upon the completion of the Phase II contract. Field tests outside of the laboratory are expected to determine both line-of-sight (LOS) and non-LOS (NLOS) capabilities.

Reports detailing the results of several analysis studies will be delivered at the end of the contract.

1.2 CONTRACT STATUS

1.2.1 Phase I

The BAA contract N66001-92-C-6010 was awarded to GTE on 30 April 1992.

The kickoff meeting was held on 21 May 1992 in Needham, Massachusetts.

The quarterly review was held on 30 July 1992.

The final review and demonstration were held on 28 October 1992.

1.2.2 Phase II

GTE was awarded follow-on contract N66001-93-C-0091 on 27 May 1993 for Phase II.

The kickoff meeting was held on 29 June 1993 in Needham.

The first quarterly review was held on 15 October 1993 in Waltham, Massachusetts.

The contract personnel and equipment were relocated to Taunton, Massachusetts, in October 1993.

The second quarterly review was held on 25 January 1994 in Taunton.

The final review and demonstration are expected to be held in late May 1994.

1.3 PRINCIPAL INVESTIGATOR

John Lovell of the GTE Government Systems Corporation is the principal investigator for this effort. He can be reached at (508) 880–4324.

Any question regarding the ISRC project should be addressed to John Yen at (619) 553–6502.

2.0 APPROACH

The GTE link for Phase I used GTE's proprietary Adaptive Sparsely Populated RAKE (ASPARK) DSSS modem, which was developed with GTE internal research and development (IRAD) funds.

The wideband DSSS technique uses a pseudorandom (or pseudonoise) sequence to spread the RF signal over a 100-MHz spread band, thus reducing the RF power spectral density, so that the signal will be hidden in the noise. The receiver uses the ASPARK to combine the signals received on three distinct paths.

The primary emphasis of this approach was to develop a system which would meet the requirements of a Local-Area Network (LAN) Backbone mission (≤1 km operations range, <2-km detection range beyond the operations range, 2.4-kbps to 1.6-Mbps data rate, $\leq 10^{-4}$ uncorrected BER, and NLOS). However, the Company Radio and Wideband Digital Link missions can ultimately be achieved with the same general approach.

2.1 FREQUENCY

GTE proposed to use the military L-Band (1.35 to 1.85 GHz) as their propagation medium because they have a license to operate at this band. This frequency selection was in addition based on factors such as the propagation range, power required, antenna size, bandwidth requirements, and expected environments. The ASPARK modem could be used with carrier frequencies in the 300-MHz to 60-GHz ranges.

A tradeoff study on the best frequency to be used for any particular scenario will be performed as part of a Phase II effort.

2.2 MULTIPATH

The ISRC mission environments will likely involve many obstructions, resulting in multipath components, spread over a maximum of roughly 5 µs. While multipath effects (fading due to destructive self-interference) are problematic for narrowband communications systems, the GTE ASPARK modem has the potential to exploit multipath effects by constructively combining the signals received on up to three paths.

The ASPARK breadboard system, previously built by GTE, will be reassembled using the 1.3-GHz carrier frequency. Modifications will also be made to obtain a 22-kbps (fixed) data rate and a 100-MHz bandwidth.

A classical DSSS RAKE receiver uses a tapped delay line with N taps spaced at the chip time Tc. For the classical RAKE to be effective, the total span of the tapped delay line must be as large as the maximum expected delay spread. The maximum expected delay spread in ISRC applications is on the order of 5 μs. GTE's chip rate for Phase II is 50 megachips per second (Mcps), thus a chip time Tc = 20 ns. To cover a maximum delay spread of 5 μs, a classical RAKE for a 50-Mcps system would require N = 250 taps.

GTE's ASPARK design is based on the fact that typically only 3 to 5 signal rays within the 5-μs spread are of significant strength to warrant synchronizing to them. Thus, rather than using a fixed delay between enough taps to span the maximum delay spread, the ASPARK uses a variable delay between enough taps to capture the maximum number of significant signal rays. This approach reduces the amount of hardware required in the RAKE, but requires an adaptive algorithm to adjust the delays between the taps in accordance with the delays of the received signal rays. In the long run, this will result in a more cost-effective and rugged system.

The GTE system identifies the strongest three components, recovers the information in those components, and then integrates them together into a total received signal. By recovering information in the strongest components, the direct component signal can be enhanced rather than degraded by multipath effects.

2.3 NLOS OPERATION

The ISRC missions may require operations without a direct path; that is, there is no line-of-sight between two terminals of a link. By the use of the indirect path components along with the ASPARK approach, GTE proposed to communicate in an NLOS mode. The indirect path components arise from reflections off various surfaces in the region between the two terminals, such as buildings, foliage, water, or natural structures. Refraction effects may also result in multipath components.

The feasibility of true NLOS capability based on the ASPARK multipath reconstruction technique shall be determined during the Phase II field tests.

Because the expected operational environment will have many sources of multipath that are not necessarily stationary, the ASPARK must also demonstrate the feasibility of reconstructing the signal from dynamically changing components.

2.4 WIDE BANDWIDTH

In the DSSS scheme, the signal is spread with a pseudorandom code (50 Mcps over a 100-MHz band) at a low power level, so that the signal hides in the noise. Even at a data rate of 1.6 Mbps, the signal can be spread with a processing gain of 15 dB into the extremely wide band employed by the GTE system. This wide bandwidth of the ASPARK was one of the major reasons the GTE proposal was selected for Phase I contract award.

The wide bandwidth results in very low signal density at any one frequency, thus a small signature for detection by an enemy. Unlike other proposed ideas based on atmospheric attenuation, the DSSS approach provides a detection range that can be less than the operations range for certain scenarios. This provides the system with its LPD characteristic.

3.0 RESULTS

The final Phase I review and demonstration was held on 28 October 1992 at the GTE plant in Needham, Massachusetts. The final review was attended by John Yen and Chuck Mirabile, who represented the project sponsor.

3.1 TECHNICAL RESULTS

The study and adaptation of the DSSS technique, from which GTE adapted the ASPARK modem for this effort, went well. The GTE progress for the contract met all the initial milestones.

3.1.1 Vulnerability Analysis

The vulnerability study made of the proposed link indicated that the link LPD characteristics are very good. The study was based on single-path worst-case scenarios using several interceptor detector technologies. In a classified appendix to the Phase I final report, vulnerability to feature extraction detectors was analyzed. The GTE system planned to implement countermeasures that reduced feature detector effectiveness below that of radiometers.

GTE generally characterized the vulnerability to intercept in terms of range ratios, which is the ratio of interception range divided by the communication range. An example was given of a 15% ratio for 64-kbps data rate, 50-MHz spread bandwidth, and Eb/No ratio of 6 (where Eb is the energy per bit and No is the noise power per hertz).

The analysis was based on SNR at the input to the potential intercept receiver. The probability of specific detection and false alarms is dependent on the intercepting system. The initial study concluded that certain general features (e.g., large bandwidth) should be incorporated into the GTE design. The GTE overall plan for the system addresses each of these features.

Further investigation of vulnerability will be made during the Phase II effort.

3.1.2 Breadboard Transmitter Test Results

The carrier suppression level of the transmitter was measured to be 34 dB. This exceeded the suppression level goal of 30 dB.

A spectrum analyzer was used to measure a bandwidth of 99 MHz by looking where the first null of the modulated carrier spectrum occurred. This value meets the required goal for the transmitter bandwidth.

3.1.3 Simulated Multipath Performance Results

Three simulated equal strength signal paths into the ASPARK demodulator showed an 87% probability with a received –21 dB carrier-to-noise density ratio. This probability was lower than the 90% theoretical acquisition probability based on a false alarm rate of 10^{-4}, but was within statistical limits for this test.

Various BER tests were performed for three general cases:

(a) Three equal strength paths;

(b) One strong path and two weak paths;

(c) Two strong paths and one weaker path (see figure C-1).

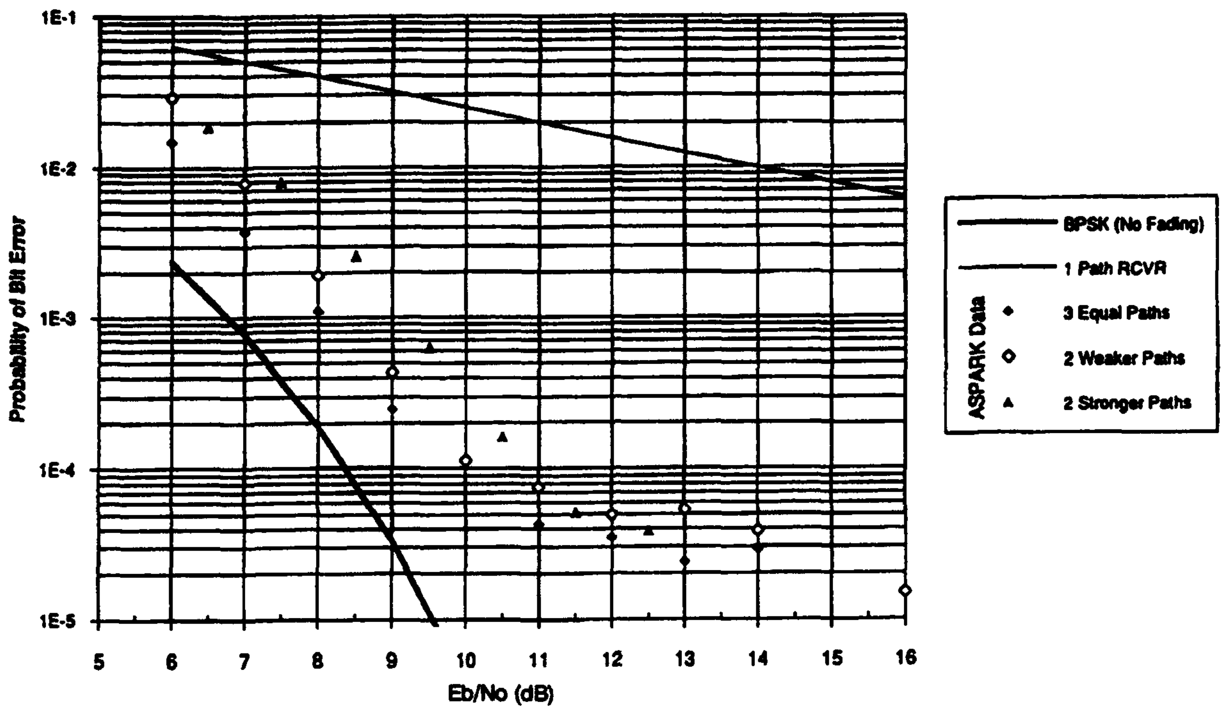

Figure C-1. ASPARK performance—multipath.

The results show that the summation of the three indirect paths is an improvement over the single path in a multipath environment (see figure C-1). A theoretical plot of a single path in a non-multipath environment (no fading) is also shown for comparison.

3.2 SATELLITE TERMINAL DEMONSTRATION

A demonstration with the Portable Satellite Terminal (PoST) showcased GTE's capability to package a system using the same DSSS waveform as the ASPARK into a fieldable system. Two PoST terminals at the Needham plant were linked through a satellite over the Pacific Ocean. Voice and faxes were sent through the link at a data rate of 16 kbps.

3.3 LABORATORY DEMONSTRATION

A laboratory demonstration with the RF/simulator breadboard consisting of seven wirewrap boards, a wired A/D converter assembly, and two RF brassboards (see figure C-2) and the ASPARK modem (see figure C-3) was performed. During the demonstration, an image (250 kilobytes, or 2 megabits) was transmitted through a multipath simulator (several cables 500 feet long connected in series, resulting in path lengths of x, x+500, x+1000 feet). This demonstrated the ASPARK adaptation's capability to reconstruct three multipath components into a coherent signal. The image was transferred at a data rate of 16 kbps, with two errors during the 2 minutes of transmission (corresponding to $1x10^{-6}$ bit error rate).

3.4 PHASE II PLANS

GTE has provided the Government with an ISRC Phase II Program Plan that covers the work to be performed during a Phase II effort. The basic plan consists of a one-way link, LOS and NLOS field test demonstrations, reports based on several analyses, and a plan for Phase III.

Figure C-2. GTE RF/simulator (Phase I).

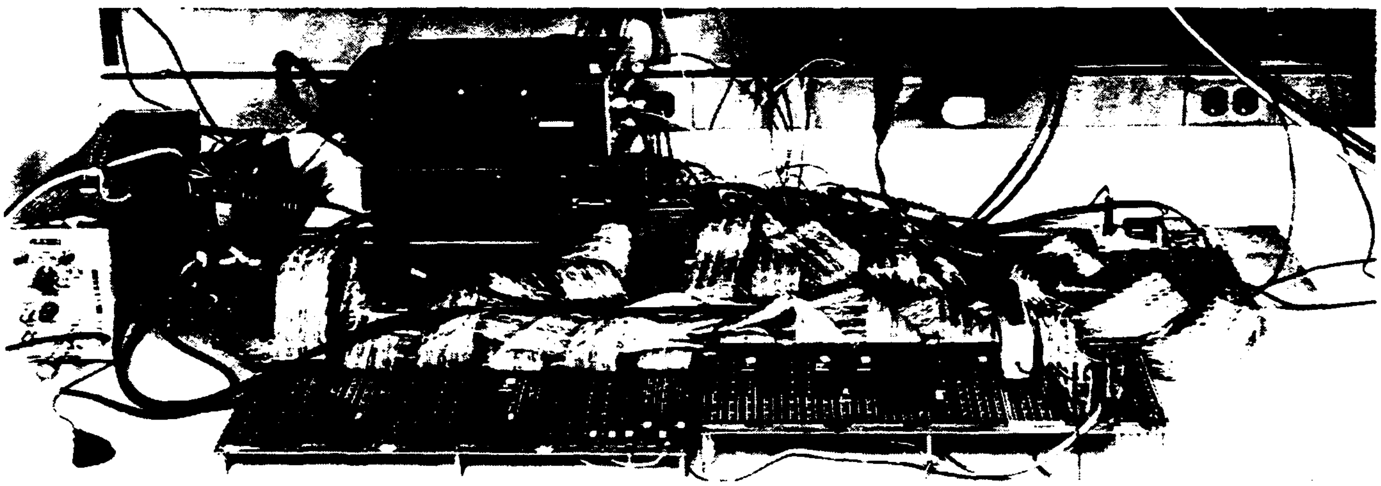

Figure C-3. GTE ASPARK modem breadboard (Phase I).

3.4.1 Field Test Demonstration

The field test will demonstrate LOS/NLOS operation outside of the laboratory with 22-kbps data rate with a 1.3-GHz carrier, 100-MHz bandwidth link designed in Phase I.

GTE plans to modify the ASPARK receiver by adding an antenna, RF front end, and automatic gain control (AGC) circuitry for operation at 1.3 GHz.

The only newly developed Phase II hardware is a portable, battery-operated transmitter.

During the tests, the receiver will remain in the laboratory and the transmitter will be moved to different locations as required.

3.4.2 Analytical Studies

A continuation of the Phase I vulnerability analysis shall be performed during Phase II.

Five separate studies shall also be made of related issues as part of the Phase II contract. These issues are transmitter safety, frequency selection, propagation, antenna selection, and power control.

The results of these studies shall all be included in the Phase II final report.

3.5 PHASE II PROGRESS

The digital design task is essentially complete and all of the parts have been ordered. GTE expects to have the field test demonstrations and all of the study reports due on schedule.

3.5.1 Hardware Status

The construction of the portable transmitter is mostly complete (see figure C-4). The transmitter uses a 1.3-GHz carrier to generate a signal with 50-Mcps chip rate and 22-kbps data rate. The transmitter consumes ≤1 W of power while transmitting through a COTS whip antenna.

3.5.2 Studies Status

The frequency selection and propagation analysis studies are in progress. The continuation of the vulnerability study has been rescheduled at a later date. The safety, antenna selection, and power control studies are expected to start in February 1994.

4.0 CONCLUSIONS

The GTE system is based on a mature technology and has a relatively low to moderate risk in developing the prototype link into fieldable equipment. The GTE system also has a high data rate and can potentially support all three USMC missions.

The main Government concern at this writing is the staffing problems with the GTE team. The reassignment of skilled personnel to the contract is expected to alleviate this concern.

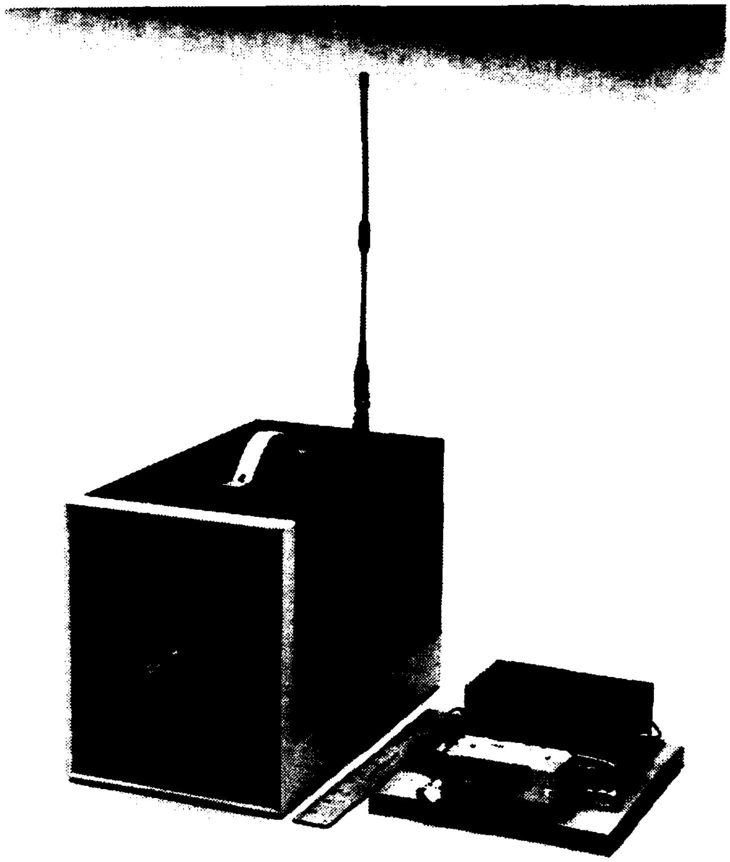

Figure C-4. GTE Phase II transmitter.

4.1 LPD/LPI

While the processing gain for 16 kbps (35 dB) results in a very strong degree of LPD/LPI, increasing the data rate to 1.6 Mbps will reduce the processing gain to only 15 dB, which may not be sufficiently LPD/LPI. Therefore, GTE must investigate other methods to increase LPD/LPI, such as reducing transmitter power and improving receiver SNR, in addition to increasing the spread bandwidth (see section 4.4).

4.2 NLOS

While its NLOS capability remains unproven, the GTE multipath reconstruction scheme provides the potential for LPD/LPI NLOS capability. The field tests during Phase II shall determine whether GTE's multipath approach provides NLOS capability.

4.3 MULTIPATH RECONSTRUCTION

The GTE simulated multipath reconstruction demonstration used regular path differences between signal components. GTE must demonstrate effective reconstruction with variable delays and realistic noise sources.

A demonstration should also be made of the capability to reconstruct the signal with dynamic delays from indirect components (reflections) produced by a moving transmitter source.

4.4 FEATURE REDUCTION

While GTE has concluded from a preliminary study that the ASPARK has a low probability of being detected by feature detectors, this must be demonstrated under realistic conditions.

4.5 POWER CONTROL

A thorough analysis of transmitter power control and potential receiver power leakage should be made for various scenarios before proceeding with a detailed vulnerability analysis.

APPENDIX D. MRC CONTRACT OVERVIEW

1.0 BACKGROUND

The Intentionally Short-Range Communications (ISRC) project advertised through the Broad Agency Announcements (BAA) for technologies that can provide low probability of detection and intercept (LPD/LPI) tactical communications.

Three contracts were awarded under the BAA solicitation N66001-92-X-6005. This appendix summarizes one BAA Phase I contract effort and the Phase II follow-on effort to date.

1.1 OBJECTIVE

1.1.1 Phase I

The Mission Research Corporation (MRC) in Los Alamos, New Mexico, proposed to develop a short-range, LPD/LPI, tactical communications system based on ultraviolet (UV) radiation propagation. MRC studied UV radiation sources and determined the optimal source for the proposed link. MRC also studied the effects of absorption and scattering on UV radiation propagation to determine the optimal parameters for the receiver components.

1.1.2 Phase II

A feasibility demonstration system will be field tested to demonstrate the feasibility of the system design developed during Phase I. MRC will deliver a one-way demonstration link upon the completion of the Phase II contract.

1.2 CONTRACT STATUS

1.2.1 Phase I

The BAA contract N66001-92-C-6007 was awarded to MRC on 6 April 1992.

The kickoff meeting was held on 22 May 1992 in Los Alamos, New Mexico.

The quarterly review was held on 4 August 1992.

The final review and demonstration was held on 5 November 1992.

1.2.2 Phase II

MRC was awarded a follow-on contract N66001-93-C-0092 on 12 May 1993 for Phase II.

The kickoff meeting was held on 9 June 1993 in Los Alamos.

The first quarterly review was held on 21 October 1993.

The second quarterly review was held on 19 January 1994.

The final review and demonstration are expected to be held in May 1994.

1.3 PRINCIPAL INVESTIGATOR

Barry Charles is the principal investigator for this effort. He can be reached at (505) 662–2133.

Any question regarding the ISRC project should be addressed to John Yen at (619) 553-6502.

2.0 APPROACH

The MRC link is based on the transmission characteristics of UV radiation in the atmosphere, which absorbs the radiation exponentially and scatters UV photons efficiently. The solar-blind region of the electromagnetic spectrum (220 to 285 nm) offers a unique low-noise spectral region in which to operate a link with very low signal, such as scattered UV light.

2.1 OZONE LAYER

The fact that ozone absorbs UV radiation in the 220 to 285 nm spectral band combined with the ozone layer in the upper atmosphere result in a spectral region virtually free of natural solar background. The low background enables the detection of the small number of photons from a UV signal, which are much smaller than the noise level for other types of radiation.

2.2 ABSORPTION

Ozone absorption in the lower atmosphere also reduces the UV signal exponentially, resulting in a very short range for UV transmissions. Such a signal will not be detectable a few kilometers beyond the operational range; thus the link will be LPD/LPI.

2.3 SCATTERING

The scattering (Rayleigh for molecules and Mie for aerosols) characteristics of UV radiation in the atmosphere diffuses a region around the transmitting beam with UV photons. Because of the low background in the solar-blind region, such scattered photons can be detected and used, so that it is possible to have a non-line-of-sight (NLOS) link under some conditions.

2.4 TECHNICAL GOALS

MRC proposed to study further the phenomena associated with UV propagation and to develop a more effective UV source based on Phase I modeling and field testing. The information obtained will be used in support of developing a Phase II system. The primary emphasis will be for local area network (LAN) applications, with an operational range of 1 km, a detectable range of 2 km, and low (2400 bps) to high (1.6 Mbps, or T1) data rates.

2.4.1 Modelling

MRC used a computer propagation model to predict the effects on the UV signal of various of the atmosphere and then compared these predictions with actual data.

2.4.2 UV Source Comparison

MRC compared UV lamps and UV lasers to determine the optimal source to use in the proposed UV link. The comparison was based on modeling, experimental data and input from laser manufacturers. The UV laser was the source selected, so the lamp requirements are not mentioned here.

2.4.3 UV Laser

MRC subcontracted with Big Sky Laser to develop and fabricate a compact transmitter package based on a quadrupled Nd:YAG laser. The laser is flashlamp-pumped, Q-switched at a

600-Hz average rate, and emits 5 mJ/pulse at 266 nm with a 10-ns pulsewidth. MRC calculated that a 0.1 mJ/pulse output will be sufficient for transmission at 2 km with a 15-degree elevation angle for both transmitter and receiver. Therefore, the laser should supply 10 times the needed energy per pulse.

The laser is air-cooled with a closed-cycle water cooling system. The power consumption will be at most 1200 W, within the BAA-specified minimum limit. A future system for Phase III can potentially incorporate a diode-pumped laser with increased efficiency, using only 200 W of prime power.

The Government instructed MRC not to proceed with a diode-pumped scheme during Phase II due to budgetary constraints.

2.4.4 Modulation

The proposed laser will have an output of 600 pps, which is too slow for acceptable voice throughput, although there is an algorithm designed to provide some limited voice communication at 800 bps.

Therefore, MRC proposed to use an 256-ary (8-bit) pulse position modulation (PPM) scheme to increase the effective throughput to 4800 bps. The system will be operating at 256 bins/pulse using approximately 1-μs bins.

The Phase III system can potentially be upgraded to 9600 bps with a diode-pumped laser.

2.4.5 UV Receiver

MRC developed an effective UV filter for the receiver and subcontracted with Barr Associates to fabricate it. The resultant filter had very good transmission characteristics in the solar-blind region with peak transmission (<5%) at 267 nm. The filter is a combination of nickel sulfate, cation-x, UG-5 glass, and a high-pass interference filter.

MRC estimated a 0.04 photoelectron/bin background noise count, assuming a 1-μs bin size, with this filter in front of the PMT. The actual background noise was measured during Phase I under various conditions and receiver orientations and will be expanded on during Phase II.

The receiver will also incorporate a 2.75-inch aperture, 3-inch imaging lens (100-mm focal length), adjustable imaging slit, 1-inch PMT (Hammamatsu R2078), photon counting preamplifier, and a circuit for detecting valid communication pulses.

The lens and aperture imaging technique was tested on a limited basis during the Phase I effort to determine the design of the Phase II system. MRC calculated that the background count can be reduced by a factor of 30 using the imaging techniques. Various PMT counting thresholds (1 to 15 counts/bin) and bin sizes (0.5 to 2.0 μs) will be used during actual field tests to determine the effects of background noise and pulse spreading on transmitter pulse recognition.

3.0 RESULTS

The final review and demonstration for the Phase I contract was held on 5 November 1992 at the MRC plant in Los Alamos, New Mexico. The final review was attended by John Yen and John Smaldino, who represented the project sponsor.

3.1 UV SOURCE COMPARISON

The MRC Phase I study of the tradeoffs between UV lamps and lasers concluded that a UV laser would provide a better source, and the Government representatives concurred. The selection was based upon a possible potential for higher efficiencies (5%) and higher repetition rates (2 MHz), compared with substantially lower typical lamp characteristics. Other benefits included shorter pulsewidths (10 ns) and lower divergence angle (< 3 mr). However, it was noted that a lamp source has a lower acquisition cost, lower maintenance cost, and simplicity that makes it an attractive option for applications that require a rugged system (such as Company Radio).

3.2 DEMONSTRATION

MRC put together a UV laser package the size of an oscilloscope that included the laserhead, drivers, fans, and water cooling unit (see figure D-1). The only external hardware was a 28-VDC power supply.

The receiver package is compact and already runs on a 10-VDC battery pack.

3.2.1 Field Test Setup

The demonstration was performed at a range of 0.5 km on a cliff behind a large building (this is an absolutely NLOS test). MRC did not have the modem as yet (to be made in Phase II) to control laser output, so only a 600-Hz laser pulse train was sent out, which was detected by the prototype receiver.

The receiver detects the UV photons, determines whether there is a laser pulse, and then displays the results on an oscilloscope. In general, the pulse train pattern was quite regular for the threshold value set.

3.2.2 Transmitter

The laser delivered by Big Sky had an output of 0.3 mJ/pulse at 600 Hz, which was only 6% of the original specification. MRC calculated a minimum of 0.1 mJ/pulse is needed for adequate reception at a 2-km distance, with a 15-degree elevation for both transmitter and receiver, and a 20-degree FOV.

The delivered flashlamp-pumped Big Sky laser performed only slightly better than commercially available diode-pumped lasers (0.3 mJ/pulse at 300 Hz have been advertised).

The use of output optics and filters (such as dichroic beam splitters) could further decrease the energy per pulse for the transmitter by an additional, but as yet undetermined, amount.

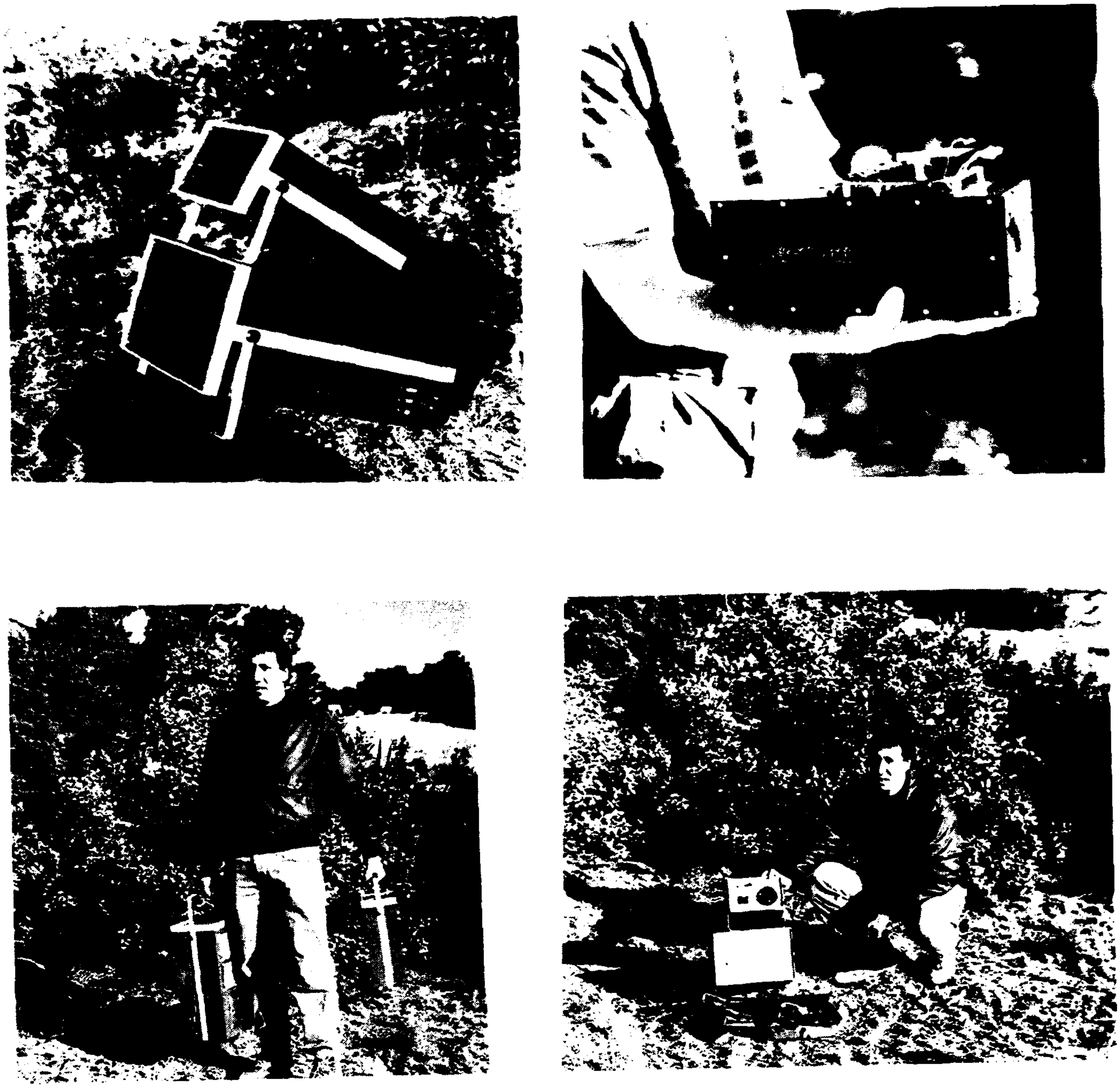

Figure D-1. MRC Phase I hardware.

3.2.3 Receiver

The prototype receiver was designed and assembled by MRC. A 10-VDC battery pack was used as the power source. The various components included a complex filter (made by Barr Associates) with 24% transmission at 266 nm, which was six times greater than originally specified (see figure D-2).

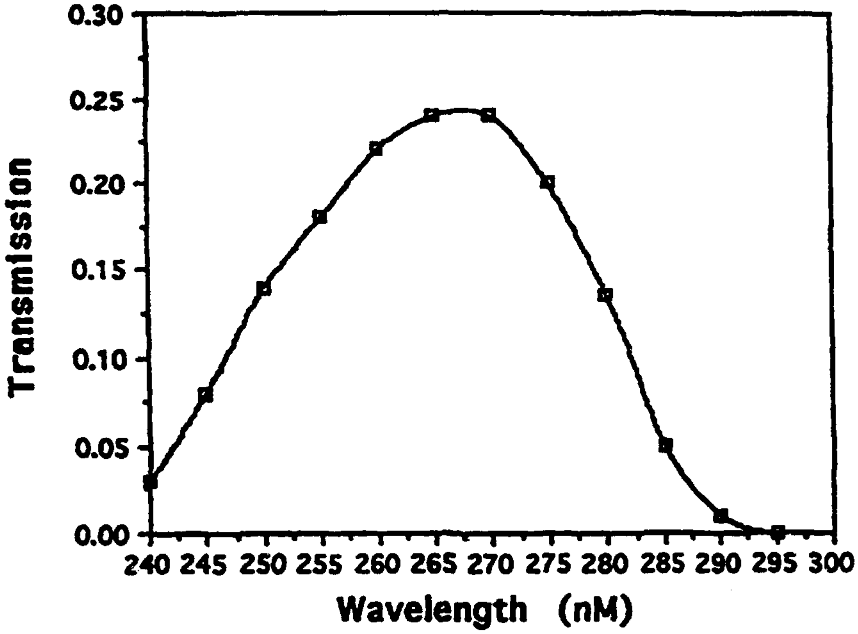

Figure D-2. Phase 1 receiver filter transmission.

The background count ranged from 2 to 60,000 counts/s, depending on the orientation of the receiver with respect to the sun. The maximum count occurred when the boresight of the detector was lined up with the sun on a "clear day." This corresponds to an average 0.06 count/bin (assuming a 1-μs bin time). This matches well with the 0.04 photoelectron/bin calculated value.

3.2.4 Field Test Results

Measurements made at a distance of 1 km were erratic and not suitable for a communication link. The signal strength at a 0.5-km distance was strong. Testing of imaging techniques were performed with and without a lens and/or aperture.

As expected, the background counts increased with the addition of a lens (22,000 counts with lens and 4615 without lens). However, signal strength decreased with the addition of the lens. More testing should reveal the source of the problem, which could be due to aberrations or simply surface loss at the lens.

Testing of the bit-error-rate (BER) at various PMT count thresholds was performed under four geometric configurations (refer to table D-1 and figure D-3).

Table D–1. MRC Field Test Configurations

Configuration	Lens	Apertured (50%)	Receiver Elevation (deg)	Transmitter Elevation (deg)
1	Y	Y	14	10
2	Y	N	14	10
3	Y	N	22	20
4	N	N	22	20

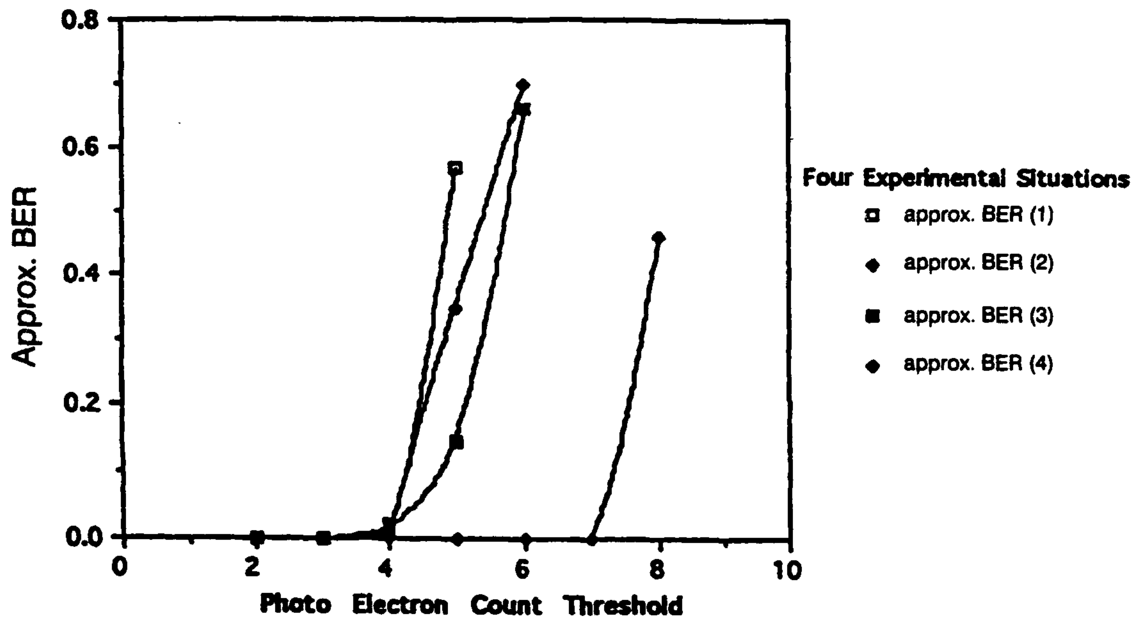

Figure D-3. Phase I receiver filter transmission.

3.3 PHASE II

MRC provided the Government with a BAA Phase II Proposal that covers the work to be performed during a Phase II effort. The Phase II plan focused on LAN capabilities, omnidirectional transmitter (360 degrees) and receiver (90 degrees) capabilities, UV laser diode possibilities, UV propagation modelling, and safety issues. The proposal estimated a cost of $42K for a new flashlamp-pumped laser and $90K for a developed diode-pumped laser ($200K proposed by Fibertek).

The Government has instructed MRC to proceed with making improvements to the current flashlamp-pumped laser for Phase II.

3.3.1 Phase II Deliverable

A field-demonstrable communication link will be demonstrated at Los Alamos with an NLOS, 4800-bps, 0.5- to 5-km range, one-way data link test.

3.3.2 Problems

Phase II work so far has indicated a problem with the 40-MHz bandwidth pre-amp, which is insufficient for the pulse-power resolution encountered during signal detection. Other pre-amps, including analog designs, are currently being investigated and tested as possible replacements.

Results of the NRaD evaluation of the receiver indicated that a 20-degree FOV is insufficient and that the current RF shielding is inadequate. MRC is presently redesigning the receiver to make improvements based on these suggestions. The filter has also been redesigned.

4.0 CONCLUSIONS

4.1 PHASE I RESULTS

The MRC progress in Phase I is impressive. The small transmitter and receiver packages indicate a good prospect for a fieldable demonstration unit. The 600-pps link at the 0.5-km field test demonstrated a completely NLOS capability. The laser design can potentially lead to more improved UV transmitter sources. The pulsewidth characteristics (<100 ns) can result in shorter bin times, which could lead to higher data rates based on the PPM scheme. The narrow optical frequency linewidth allows for an efficient filter designed specifically for the transmitter's wavelength. The potential for tunable lasers would also allow for single and efficient multichannel transmitters.

4.2 LASER POWER

However, there is still some concern for the limited energy per pulse and repetition rate of the present Big Sky laser used by MRC. Higher pulse energy lasers may take significant time and money to develop, especially if they are to be operated at higher repetition rates. For example, the Quantronix flashlamp-pumped laser acquired by NRaD was designed for higher repetition rates and produced <0.2 mJ/pulse of UV at 2.5 kHz (35 A/208 VAC, external chilled water intake).

4.3 LASER RATE

It should be noted that the maximum instantaneous rate is the inverse of the minimum dead time between pulses. For example, 9600 bps for a 1200 pps average rate yields an actual maximum rate of 1732 pps (assuming 1 μs/bin). Therefore, the design for future laser transmitters should have a minimum frequency limit equal to the maximum instantaneous rate.

4.4 PULSE SPREADING

There is also some concern for the amount of temporal pulse spread between the transmitter and receiver during the proposed 1-μs bin time. MRC's estimate (single scatter) of a 0.4-μs spread was based on a 1.5 km separation, 20-degree FOV receiver, and 15-degree elevation angle for both transmitter and receiver. However, the same model suggests that for a 2-km separation and a 40-degree FOV at 30-degree elevation, the pulse spread would be >2 μs. This suggests that the larger FOV requirement may be a problem for the proposed bin size ranging from 0.5 to 2.0 μs at the longer path lengths.

4.5 PHASE II

Phase II shall demonstrate the ability of the MRC link (see figure D-4) at several propagating distances and geometric configurations. MRC shall determine the effects of energy per pulse and pulse spreading on signal recognition and propose a optimized design for Phase III.

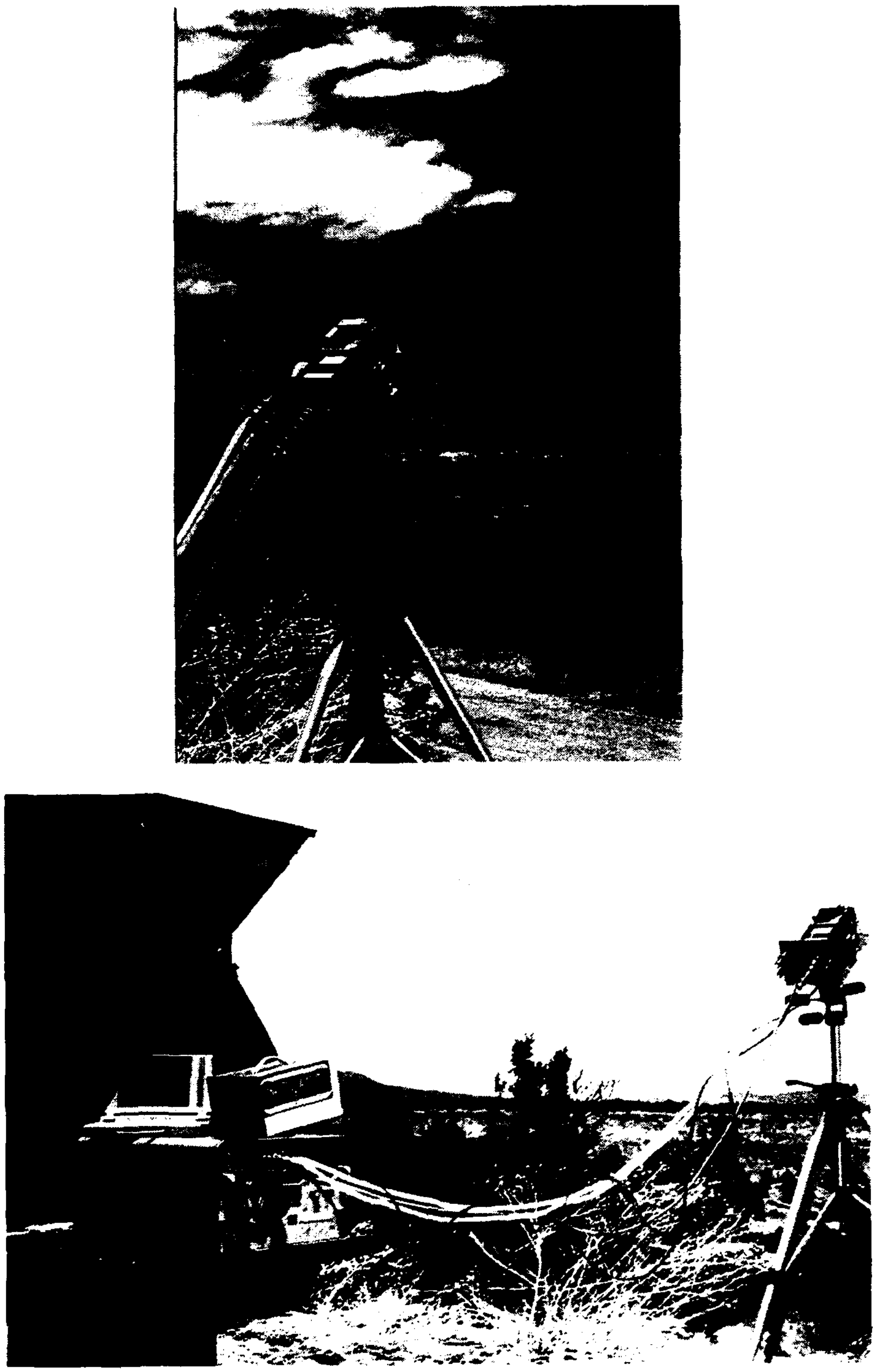

Figure D-4. MRC Phase II system.

APPENDIX E. SPARTA CONTRACT OVERVIEW

1.0 BACKGROUND

The United States Marine Corps (USMC) and the Intentionally Short-Range Communications (ISRC) project solicited through the Small Business Innovation Research (SBIR) for technologies that can provide low probability of detection and intercept (LPD/LPI) tactical communications.

One Phase I contract was awarded under SBIR solicitation N911-308. This appendix is a summary of the Phase I SBIR contract effort and the Phase II follow-on effort to date.

1.1 OBJECTIVE

1.1.1 Phase I

Sparta, Incorporated, Laser Systems Laboratory of San Diego, California, proposed to develop a short-range, LPD, tactical communications system based on ultraviolet (UV) lamps. Sparta evaluated various UV lamps and incorporated the optimal one in the link design.

Sparta delivered a system design at the end of the contract. This design was based on the surface discharge technology developed by the Sparta Lexington, Massachusetts division. They believed that this technology will provide superior performance in comparison to the lamps of the original design (unsolicited proposal by General Dynamics Laser Systems Laboratory (RENLOS)). Also, Sparta developed a propagation code and performed analyses of the proposed link.

1.1.2 Phase II

Sparta proposed to develop a UV communications link using the surface discharge technology. An ISRC system as specified under the statement of work must strive for the following characteristics.

(a) It must cover a range of 0.5 to 5 km and not be detectable 2 km beyond the operations range. Note that the Company Radio range requirement is 0.5 km.

(b) It must establish non-line-of-sight (NLOS) communications. For the system to be practical, it shall operate with buildings and other obstacles in the direct path between the transmitter and the receiver.

(c) It must operate from the available power (<100 A at 24 VDC) on a High-Mobility Multipurpose Wheeled Vehicle (HMMV) and be ruggedized for field use.

(d) It shall have a minimum data rate of 2400 bps for acceptable voice communications.

Phase II contract options exercised included a system safety study and an updated version of the Sparta propagation model.

Sparta will test and demonstrate a breadboard system, which is a one-way system consisting of a filtered transmitter and appropriate cooling system, a receiver with a solar-blind filter, and modems. System test results shall be compared with theoretical calculations and documented in a final report. The final report shall include a Phase III design.

1.2 CONTRACT STATUS

1.2.1 Phase I

The SBIR Phase I contract N66001-92-C-7007 was awarded to Sparta on 30 January 1992.

The kickoff meeting was held on 11 March 1992 in San Diego.

In May 1992, Sparta requested an extension of the contract to 6 November 1992; the request was granted.

The quarterly review was held on 25 August 1992.

The final review and demonstration was held on 3 November 1992.

1.2.2 Phase II

Sparta was awarded follow-on contract N66001-93-C-0090 on 27 May 1993 for Phase II.

The kickoff meeting was held on 24 June 1993 in San Diego.

The first quarterly review was held on 18 October 1993.

The second quarterly review was held on 27 January 1994.

The final review and demonstration are expected to be held in late May 1994.

1.3 PRINCIPAL INVESTIGATOR

Richard Morton of the Sparta Laser Systems Laboratory is the principal investigator for this effort. He can be reached at (619) 455–1650.

Any question regarding the ISRC project should be addressed to John Yen at (619) 553–6502.

2.0 APPROACH

The proposed Sparta link is based on the propagation characteristics of UV radiation in the atmosphere, which absorbs the radiation exponentially and scatters UV photons efficiently. The solar-blind region (220 to 285 nm) of the electromagnetic spectrum offers a unique low-noise spectral region in which to operate a link with very low signal, such as scattered UV light.

For this purpose, they have proposed to use a surface discharge device. This technology was developed at their Lexington lab. Some preliminary analysis comparing it favorably to the more traditional flashlamp technology was given in the Sparta Phase I report.

The final design for Phase II used a modified spark plug as the transmitter. To accommodate low pulse repetition rates, a differential pulse position modulation (DPPM) scheme was used for an effective throughput of 2400 bps.

2.1 UV CHANNEL CHARACTERISTICS

Ozone absorption of UV radiation in the solar-blind band combined with the ozone layer in the upper atmosphere result in a spectral region virtually free of natural solar background. The low background enables the detection of the small number of photons from a UV signal. This signal is much smaller than the noise level for other radiation types. A photomultiplier tube (PMT) with a solar-blind filter provides a good receiver in this spectral region.

2.1.1 LPD

Ozone absorption in the lower atmosphere also absorbs the UV signal exponentially, resulting in a very short range for UV transmissions. The signal will not be detectable a few kilometers beyond the operational range, thus the link will be low probability of detection (LPD). The actual range of communications (and detectability for the enemy) is dependent on local atmospheric conditions, principally the local ozone concentration.

2.1.2 AJ

The strong ozone absorption also means that potential UV noise sources must be within 1 km of the receiver to affect communications, thus the system is antijam (AJ). Such noise sources include explosions, arc welding, fires, and thunderstorms.

2.1.3 NLOS

The scattering characteristics of UV radiation in the atmosphere also make possible a region around the transmitter that the UV photons permeate. Because of the low background, such scattered photons can be detected and used. Therefore, it is possible to have an NLOS link under some conditions. It is expected that this system will be able to function with buildings and other obstacles in the path between transmitter and receiver.

2.1.4 Pulse Spreading

The scattering characteristics of UV radiation can also lead to significant pulse broadening and thus fundamentally limit the data rates achievable with this system. Single scattering is most likely to dominate. Where the transmitter and receiver are roughly pointing at each other, one can calculate the pulse broadening of the signal using simple geometric arguments. It can be shown that if the transmitter (roughly collimated) and receiver (with a 30-degree field of view) are confined to elevation angles of 35 degrees or less, then pulse spreading will be less than 0.757 μs/km of ground path separation. If the elevations are both confined to be 45 degrees, it is a maximum of 1.263 μs/km.

As the elevation angles increase, or the transmitter is pointed far off axis, this spreading can increase rapidly. In these cases, the length of the propagation path, rather than the geometry, eventually will limit the spreading. For this reason, one can expect an omnidirectional transmitter to potentially have very large pulse spreading.

2.1.5 Pulse Rate

In general, second-order scattering is not of concern. Usually, it will be orders of magnitude below first-order scattering in energy and can easily be 10's of μs wide. Therefore, the broadening due to first-order scattering fundamentally limits the pulse repetition rate that can be achieved in the UV.

Pulse repetition rates are limited in both flashlamp and surface discharge devices by pulse shape, pulsewidth, practical average power, and temporal control considerations.

2.1.6 UV Channel Summary

The UV channel is an ideal choice for NLOS, LPD, short-range communication systems. However, pulse spreading fundamentally limits the channel data rate to, at best (unlikely to be reached) a maximum of 500,000 pulses per second on a 1-km path. Thus, a 2400-bps link can be accomplished straightforwardly, but a 1.6-Mbps link is not practical.

2.2 SURFACE DISCHARGE DEVICE

The surface discharge device was developed by the Sparta Lexington Laboratory. A high voltage is applied across a dielectric material, and the resulting electric current is confined to a thin sheet of plasma adjacent to the surface of the dielectric, which reaches a very high radiating temperature and produces a very efficient and broadband output. Some of the dielectric material is vaporized and contributes its line spectra to the output radiation.

It was stated in the Phase I report that chromium oxide, Cr_2O_3, would be a good choice of material for the spectral range of 250 to 280 nm, presumably because of its spectral characteristics. It was mentioned that chromium oxide should have a long lifetime because of its low vapor pressure.

2.2.1 Phase I Devices

In the Phase I study, the Lexington group compared a 1-inch surface discharge device of Teflon against Sparta's Cermax flashlamp using a "solar-blind" filter. The surface discharge was found to be 78% more efficient. This is subject to some uncertainty because Sparta's integrating sphere was actually a box covered with a paint of unknown spectral characteristics. The results might be partially explained by the distinct possibility that the flashlamp is collimated while the surface discharge device was not. Therefore, the beam paths to the receiver may have been shorter than expected (longer paths having been attenuated out by a poor choice of paint). However, it is significant that these sources have comparable UV energy in the band of interest.

2.2.2 Phase II Device

In the Phase II design, Sparta plans to use a modified alumina ceramic spark plug as a surface discharge device. The principal modification will be to machine the electrodes to ensure that the discharge occurs at the surface of the dielectric rather than in an unconfined manner through the fill gas (see figures E-1 and E-2). The steel ring of the sparkplug will be replaced with a ring of molybdenum, which is a better electrode material.

2.2.2.1 Advantages. The above design will have many advantages. Even with a minor amount of machining, a spark plug is cheap, compact, rugged, and designed to function at high temperatures and rates. For instance, it should have a faster rate and a shorter pulsewidth (100 ns) than a flashlamp. When a device wears out, it may be field–replaceable at low cost.

2.2.2.2 Disadvantages. One difficulty is that significant broadband radiation outside the solar-blind is generated and must be filtered to avoid detection or interference. Filtering will generate heat in addition to the heat generated by the spark plug itself. The heat must be dissipated for a practical system, and Sparta is addressing these concerns in the Phase II design.

2.2.2.3 Initial Measurements. However, Sparta has just presented some initial measurements of the spark plug device that were encouraging (see figure E-3). These are the first spectral measurements of the spark plug emission in the UV communications band. They measured 18% output of radiated light in the solar-blind UV band (250 to 300 nm), with an estimated 20 mJ/pulse in this band, and a pulsewidth of 1.5 μs. The device was operated in xenon gas at about 1.7 atm. Whether it can ultimately be operated in air is unknown at this time.

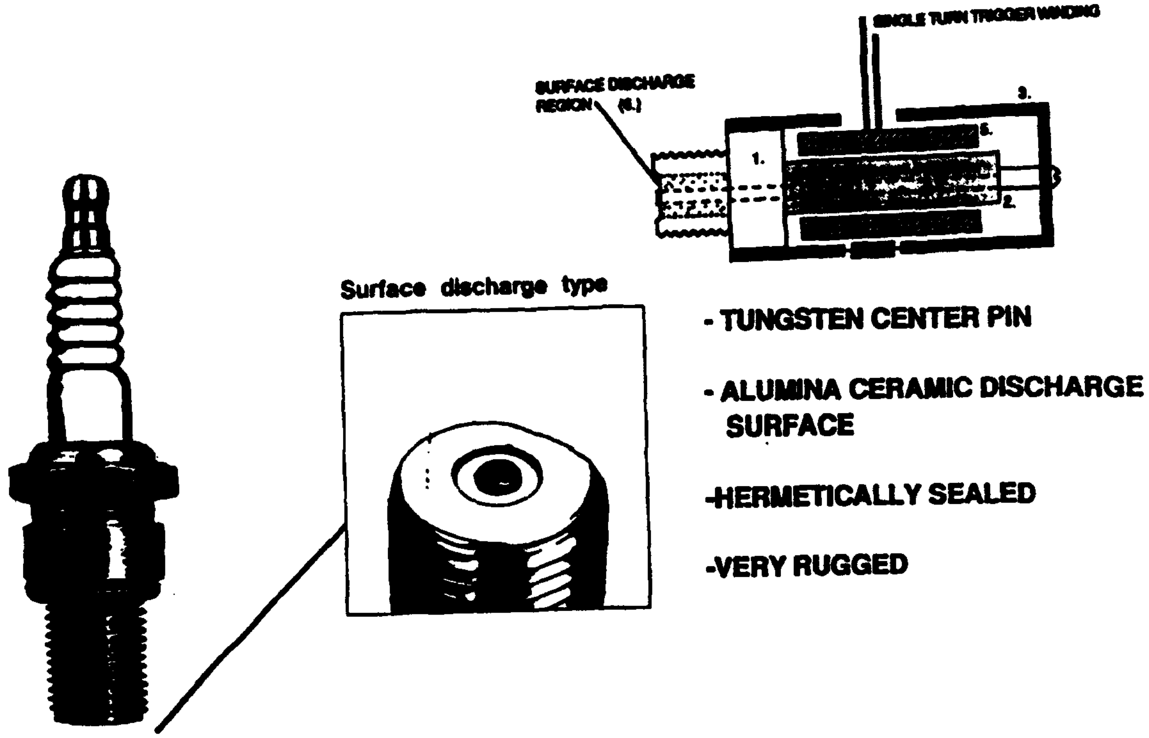

Figure E-1. UV source synonym: "sparkplug."

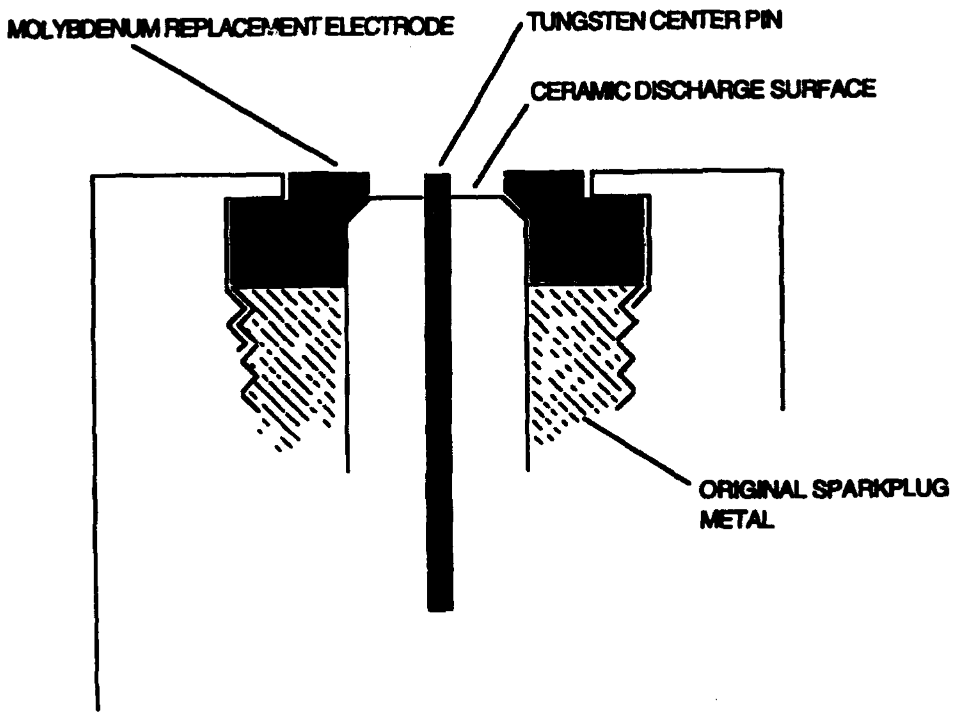

Figure E-2. Sparkplug modification.

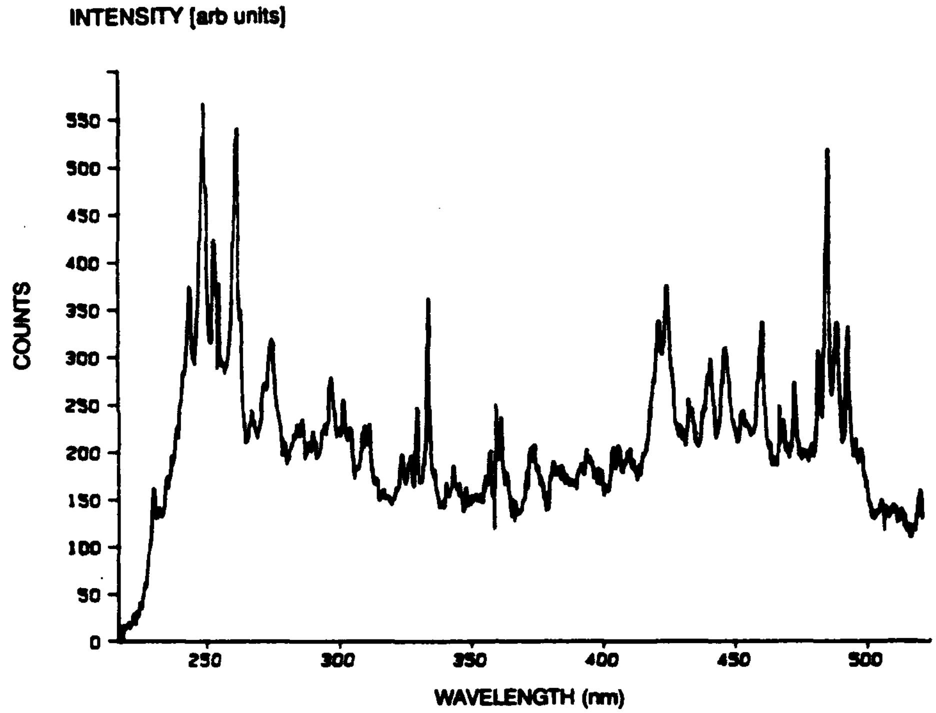

Figure E-3. Sparkplug spectrum (initial results).

2.3 DPPM

Because of the relatively low pulse repetition rate, Sparta is using a differential pulse position modulation (DPPM) scheme to code its signal at 2400 bps.

The DPPM scheme has the advantage that more information can be sent with a relatively small average pulse rate. This will allow more time for charging the device, reduce the heat generated, extend the life of the source, and reduce power needs. However, the disadvantage of this scheme is that if a noise pulse appears, it can destroy several bytes of information by confusing the positioning. This can be alleviated with some good error detection and correction algorithms.

2.3.1 Vocoder

The vocoder was expected to be an off-the-shelf item. Unfortunately, no vendor is making modulators for such slow data rates today because of lack of demand for data rates lower than 9600 bps. However, Wintriss Engineering of San Diego was willing to fabricate the vocoder cards. Delivery is expected in February 1994.

2.3.2 Design

In the Sparta design, an average of 310 Hz (including synchronization) is used to encode an average of 2400 bps. Each pulse will represent 8 bits in a 256-ary scheme. The value of each 8–bit byte is encoded in the time position of each pulse with respect to the previous pulse. The minimum time between pulses represents a value of 0 (00000000).

The average pulse rate of the data will be 300 Hz. The remaining 10 Hz of the average pulse rate of 310 Hz are used for the 10-Hz synchronization frame.

The 5-μs bin size should be ample for most likely scenarios of pulse broadening in the UV. One would like the bin size to be about double the worst-case pulsewidth. Programmability in

the boards will allow the time bin size and other parameters of the DPPM algorithm to be changed. For instance, should it turn out that pulse spreading operationally is significantly less than 2.5 μs, one may reduce the bin size and operate at a higher data rate. However, 5 μs appears like a practical choice at this time.

2.4 FILTERING

The Sparta design will require some sophisticated filtering on both the receiver and transmitter.

As noted above, to maintain LPD and to prevent interference with other equipment, the broadband RF transmission must be filtered carefully. One way to do this is with a low optical loss ground plane EMI screen on the transmitter. The receiver must be carefully filtered as well to maintain the good signal-to-noise characteristics of the solar-blind UV band. It is desirable that both filters be broad in the solar-blind band, because the transmitted spectrum is so broad.

Whatever the final Sparta design, it is likely to decrease the signal significantly. Fortunately, initial results indicate a strong signal from the sparkplug.

3.0 RESULTS

The final review for the Phase I contract was held on 3 November 1992 at Sparta. The final review was attended by John Yen, Debra Gookin, and John Smaldino (who represented the project sponsor).

3.1 MODELING

3.1.1 Phase I

As part of the Phase I effort, Sparta used an inhouse computer propagation model to predict the effects on the UV signal of various parameters of the atmosphere and then compare these predictions with some actual data. Also studied was the practicality of an omnidirectional system.

Few details have been given so far about their model. However, it does (optionally) include second-order scattering and transmitter and receiver parameters. The second-order scattering was found to be usually insignificant when compared to the first-order.

3.1.2 Phase II

As part of the Phase II contract, Sparta will update some of its scattering and absorption parameters used in the model to reflect more recent data.

Modeling has yet to be done on the current Phase II system. Sparta will probably need to know more about the transmitter power output and the receiver sensitivity with all its optics before starting further analyses.

3.2 HARDWARE

In the Phase I final report, Sparta estimated that a ruggedized manpack transmitter system will weigh 40 pounds, have a volume of 1 ft^3, and require 330 W during transmission.

3.2.1 Power

Since the transmitter will operate in bursts of a few seconds, a 5-pound lithium battery pack that can supply 550 W-hr will provide adequate power. The receiver would only require 30 W during operations. The receiver and transmitter are both switchable to operate from either HMMV power or a battery pack. They will use power conversion modules to convert from the HMMV power to the requirements of each of the modules.

3.2.2 Electronics

Sparta is using a modular design, designing for compactness and ruggedness.

3.2.2.1 Vocoder Module. The vocoder electronics module is the same for both the receiver and transmitter. It will be small (6x8x2 inches), weigh 0.5 pound, and consume less than 5 W.

3.2.2.2 Transmitter Module. The transmitter will need two more major electronics modules: a capacitor charging power supply and the source trigger circuitry. A programmable capacitor charging power supply that can operate from a 28-VDC input and produce up to 20 kV at an efficiency of at least 85% has been ordered. The source trigger circuitry accepts TTL input (from the vocoder), uses a 12-VDC power supply, and has triggered light pulses from a volume discharge device with a pulsewidth of 400 ns.

3.2.2.3 Receiver Module. The receiver will need a high-voltage supply and preamp electronics for the PMT. A Cockroft-Walton power supply is extremely compact, will run with 12-VDC input, has a low power draw, and is likely to add less dark current to the PMT than a traditional source. Sparta will build inhouse the PMT opamp to convert the PMT output to a TTL pulse for the vocoder. The receiver is shown in figure E-4.

The PMT (Hammamatsu #R1893) will have a parabolic light concentrator to bring its field-of-view (FOV) up to 30 degrees and improve its efficiency. The PMT was selected for its low dark current characteristics, small size, and high gain.

3.2.3 Risk Factors

Some of the hardware risk factors include filter design, heat dissipation at the transmitter, electromagnetic interference, and sparkplug lifetime.

It may be difficult to design a filter for the correct spectral range that does not excessively decrease the signal. However, it appears at this point that Sparta will have a strong signal with which to work.

3.3 SAFETY

The safety study has not been performed as yet. A study of the spatial distribution of the emitted power and the energy densities to determine eye safety risks to personnel shall be made. This information shall be used in the Phase III transmitter design. It is expected that this system is less hazardous than a UV laser because of the greater beam divergence and the longer pulse-width. No mention was made of any assessment of long-term cancer risks.

4.0 CONCLUSIONS

There is a good likelihood all Government technical objectives can be met in Phase II except a high data rate of 1.6 Mbps (which is impossible for this technology). Most of the electronic modules being acquired are off-the-shelf items, and are inhouse or on order.

4.1 EMITTER

The sparkplug UV emitter link looks like an innovative and promising system for the Company Radio. Sparta is planning to screw the sparkplug emitter into the optics assembly for easy reusability.

4.2 VOCODERS

The Wintriss boards have their own processor and are expected to be very flexible and programmable. Wintriss specifically mentioned that these boards can be reprogrammed for error correction and to allow future two-way push-to-talk (half duplex) communications using a single board.

4.3 UV FILTER

Sparta has investigated a number of filter materials and has developed some preliminary ideas on filtering. It remains one of the more difficult items they have left to address.

4.4 OPTIMIZATION

Since many parts of the design have been optimized in Phase II, it is possible to reduce the weight and power requirements substantially.

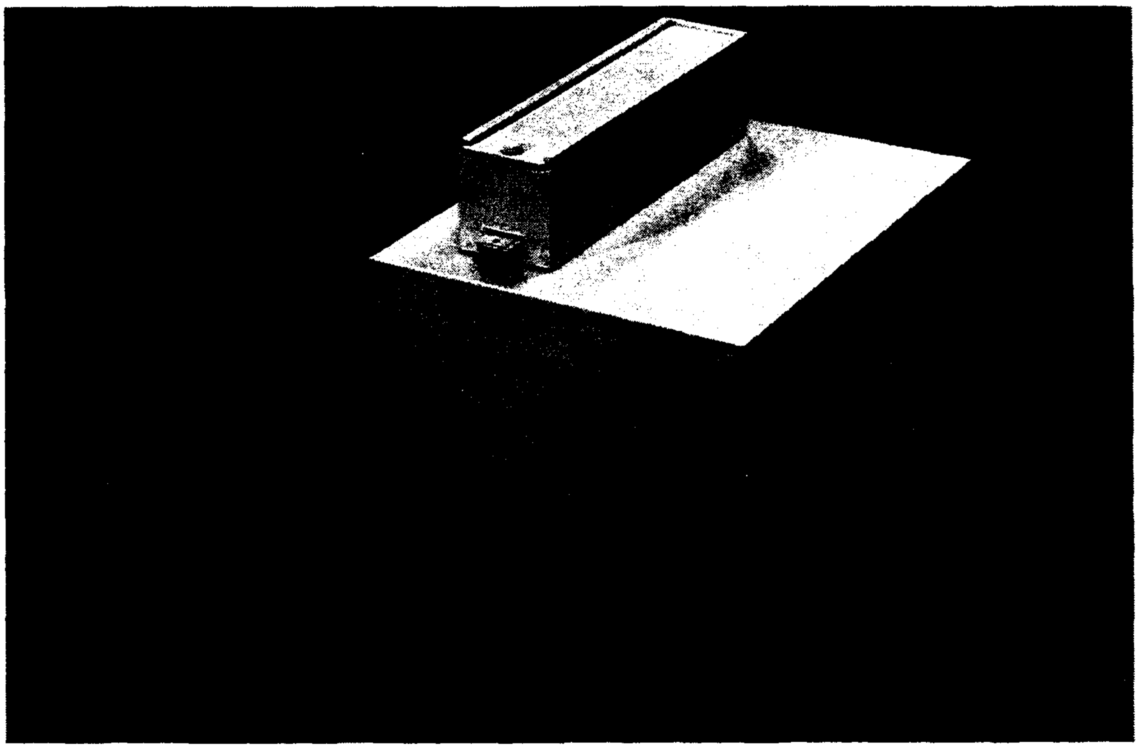

Figure E-4. Sparta Phase II receiver.

APPENDIX F. TITAN CONTRACT OVERVIEW

1.0 BACKGROUND

The Intentionally Short-Range Communications (ISRC) project advertised through the Broad Agency Announcements (BAA) for technologies that can provide low probability of detection and intercept (LPD/LPI) tactical communications.

Three contracts were awarded under the BAA solicitation N66001-92-X-6005. This appendix summarizes one BAA Phase I contract effort.

1.1 OBJECTIVE

The Titan Systems Group in San Diego, California, proposed to develop a short-range, LPD, tactical communications system based on an infrared (IR) laser diode array emitting in the water absorption band about 1.39 μm. Titan would deliver a design for the proposed link at the end of the Phase I contract.

1.2 CONTRACT STATUS

The BAA Phase I contract N66001–92–C–6005 was awarded to Titan on 14 May 1992.

The kickoff meeting was held on 3 June 1992 in San Diego.

The quarterly review was held on 3 August 1992 in Albuquerque, New Mexico.

The final review and demonstration were held on 6 November 1992 in Albuquerque.

Titan was not selected for the Phase II follow-on effort.

1.3 PRINCIPAL INVESTIGATOR

Jeffery Puschell is the principal investigator for this effort. He can be reached at (505) 764–5315 in Albuquerque, New Mexico.

Any question regarding the ISRC project should be addressed to John Yen at (619) 553–6502.

2.0 APPROACH

The proposed Titan link is based on the transmission characteristics of IR radiation in the atmosphere where water vapor absorbs the radiation exponentially.

2.1 ABSORPTION

Water vapor has many absorption bands in the atmosphere, where the attenuation coefficient increases by many orders of magnitude. By selecting a wavelength on the edge of one of these bands, centered at 1.39 μm (see figure F-1), Titan proposed to build a link that is completely attenuated a short distance beyond the operation range (<5 kilometers).

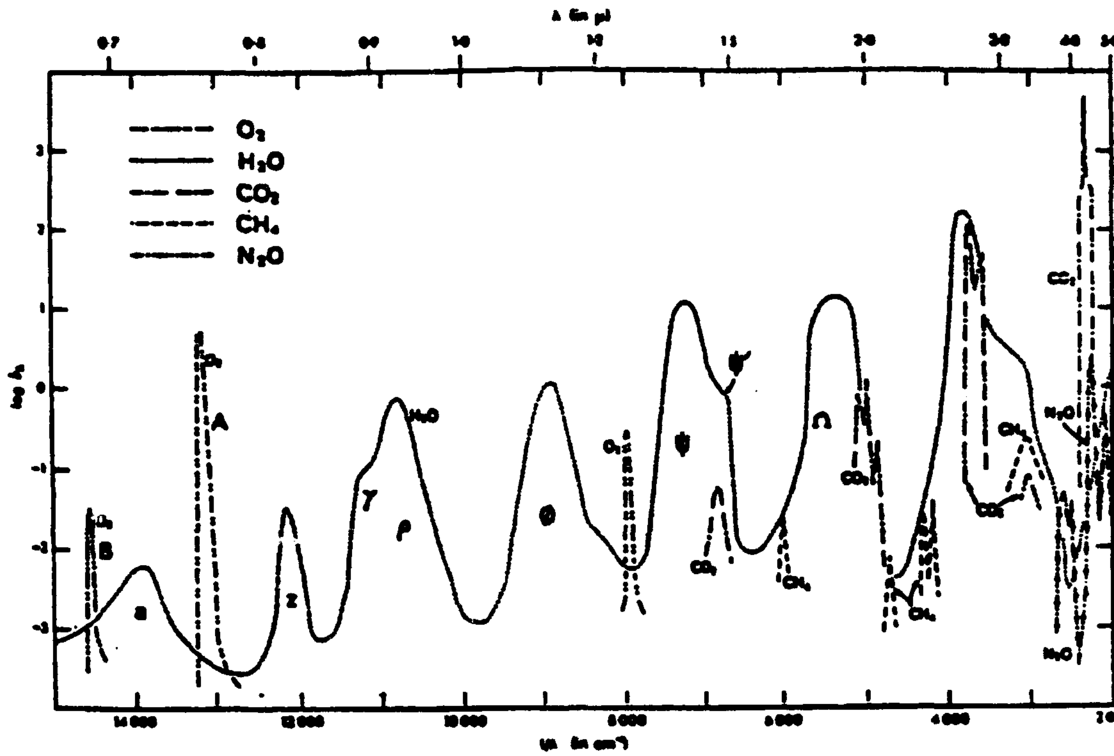

Figure F-1. IR band absorption of atmosphere gases.

By being on the edge of the band (wavelength of about 1.32 to 1.35 µm), Titan can theoretically vary the range by varying the wavelength (see figure F-2). For example, the theoretical predictions for 30-km visibility and Phase II power levels result in a 2.2-km communications range and a 2.7-km detection range at 1.335 µm. The same model predicts a 1.4-km communications range and a 1.7-km detection range at 1.321 µm.

2.2 LASER DIODE

Titan proposed to build an InGaAsP laser diode assembly that can be tuned to emit at a wavelength between approximately 1.32 and 1.35 µm (not easily made although 1.3 and 1.55 µm are commonly used wavelengths). Titan subcontracted with the David Sarnoff Research Center to fabricate a tunable laser diode with center wavelength of 1.335 µm and tuning range of ±0.013 µm. The center wavelength was not to vary more than 5 nm. The linewidth was to be less than 10 nm (including chirping).

2.2.1 Diode Specifications

Several specifications were requested in order to comply with the BAA requirements. The minimum average power was to be 100 mW over the entire tuning range. The far field divergence full angle was to be no more than 10 and 40 degrees for parallel and perpendicular directions, respectively. A cylindrical lens would be used to reduce the perpendicular divergence to 10 degrees to ensure a ±5 degree off-boresight transmission. The pulsewidth was to vary from 250 ns to 450 µs. The average pulse repetition frequency was to vary from 10 Hz to 2 MHz. The total current consumption was to be less than 3 A.

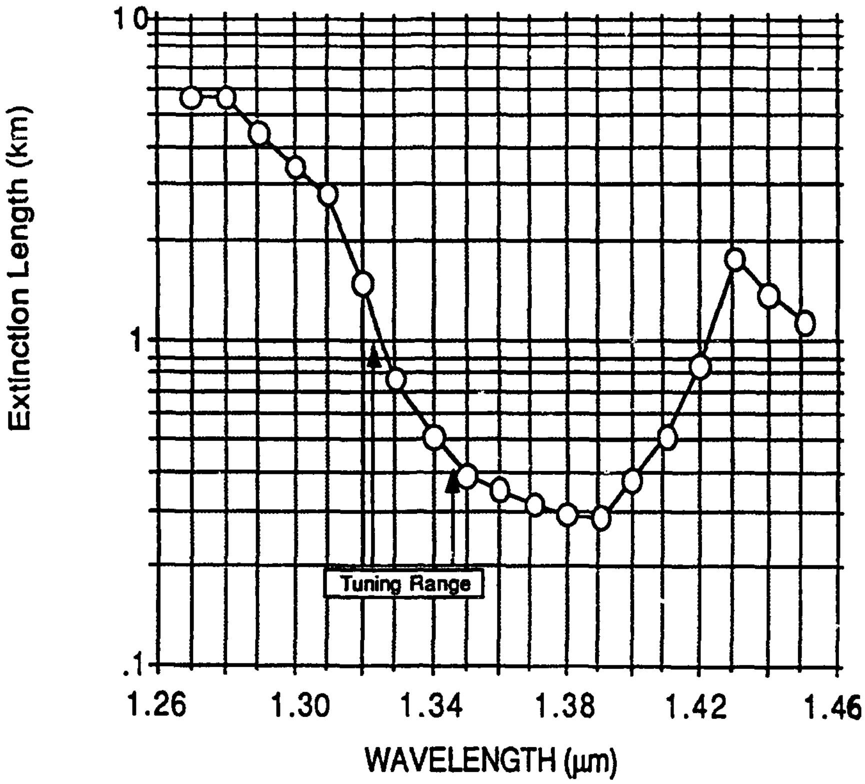

Figure F-2. Extinction length vs. wavelength for 1.390-µm band on Titan's model.

2.3 TUNING

The laser center wavelength is tuned by varying the temperature of the diode. To obtain the wavelength range, the diode temperature must be controllable in the range between −20 to +50 degrees C. To keep the center wavelength stable, the temperature must likewise be stable.

Since the wavelength gradient of the laser diode is about 0.4 nm/degree C, the temperature must be maintained in a 5-degree C range for the center wavelength to remain within ±1 nm. The proposed design would incorporate both a water-cooled backplate and a thermoelectric cooler (ILX LDM-4412 mount and ILX LDC-3742 temperature controller) to maintain temperature stability.

2.4 MODULATION

Titan used a pulse generator to modulate the laser diode. The laser diode has the potential of being modulated at rates of up to 20 MHz, although a practical rate on the order of a few megahertz is likely. This high potential data rate will more than satisfy the ISRC data rate requirements, and indicates that this system should be targeted toward the missions needing higher data rates.

Titan proposed to use a pulse generator (Phillips PM5715) to modulate the laser diode, and envisioned using a pulse position modulation (PPM) scheme to code actual data for a Phase II effort.

2.5 RECEIVER

Titan proposed to use a 2-mm diameter InGaAs PIN photodiode (EG&G C30642E) behind an interference filter (Spectrogon BP-1330-080-B of 80-nm bandwidth or BP-1330-030-B of 27-nm bandwidth) and focusing lens (12-mm diameter, 8.5-mm focal length), with a 12-degree field-of-view (FOV) custom-made receiver assembly.

Titan proposed to use 10 of these assemblies together during a Phase II effort. All parts are commercially available.

2.6 POWER CONSUMPTION

The proposed Titan link's power requirement, on the order of 500 W for a two-way link in Phase III, is well within the power specification listed in the BAA solicitation (<100 A, 27 VDC).

2.7 ANGULAR SPREAD

The laser diode was designed to emit at a large angular spread, on the order of 10 degrees. This coupled with a wide FOV detector will alleviate some of the difficulties associated with aligning line-of-sight (LOS) systems. However, because of the weak molecular IR scattering characteristics and the natural IR background, the Titan link will have a low probability of ever operating in a strictly non-line-of-sight (NLOS) mode.

3.0 RESULTS

The final review and demonstration was held on 6 November 1992 at the Titan plant in Albuquerque, New Mexico. The final review was attended by John Yen and John Smaldino, who represented the project sponsor.

3.1 TECHNICAL

The technical briefing was done well, with the IR laser diode subcontractor (Sarnoff) participating.

3.1.1 Output Variations

The laser diode characterization was performed well, although a question remains as to the reason for variations in output power for the parallel beam profile associated with the 20-μm-wide laser diodes. This "rabbit ear" profile could possible be due to backreflections from the cylindrical lens, but are most likely due to the number of lateral modes, which increases with the square of the laser diode width.

This problem is expected to exist also for the 20-μm-wide lasers proposed for the Phase II effort. Titan will need to make more measurements to confirm the origin of the problem.

3.1.2 Temperature Control

Government reservations about the ability of Titan to maintain diode temperature stability remain unanswered and indicate that Titan and Sarnoff should further investigate other methods of temperature control during Phase II.

3.1.2.1 Phase I. Other methods such as microchannel cooling have been proposed in the Phase II plan. The temperature controller used during Phase I could only stabilize the temperature down to –9.4 degrees C. The power supply used could not supply enough current for 50% modulation at 250-ns pulsewidth (4 MHz) at higher temperatures (+30 and +50 degrees C) and the duty cycle was reduced to 10% (400 kHz) for measurements above +15 degrees C. Therefore, measurements in the laboratory for a stable temperature at a minimal 2-MHz modulation were only over a –9.4 to +15 degrees C range which would correspond to a ±5–nm tuning range maximum (assuming 0.4-nm/degree C shift).

3.1.2.2 Laser Cavity. Various cavity lengths and widths of the laser diodes were investigated to provide the best center wavelength (1.335 µm) and power characteristics (>100 mW) while providing a spectral linewidth less than 10 nm. The multimode output characteristics of the final laser design during Phase I (20x1000 µm) varied from one laser to another (6- to 7-nm linewidth FWHM).

3.1.3 Spectral Variation

Each laser has a spectral characteristic that is dependent on temperature and modulation duty cycle. The calculated length of atmospheric attenuation for various wavelengths between 1.3 and 1.4 µm is based on a somewhat smooth curve (see figure F-2).

Theoretical plots based on modeling at NRaD (urban and rural conditions) on a 4-nm resolution show more variation within the same range (see figure F-3). This complex relationship identified by the NRaD model, coupled with the changing spectrum of the laser diodes, would make realistic calculations of the detection range difficult to determine at the various temperature levels. An average wavelength and a corresponding average extinction length could perhaps be assumed, especially for the Phase II multi-diode approach.

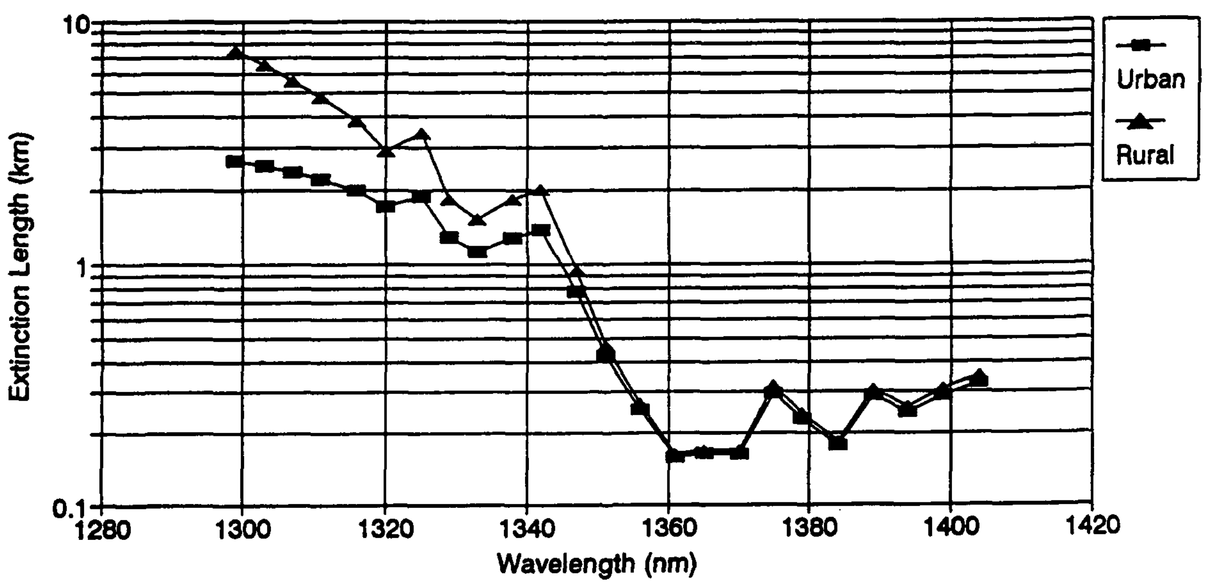

Figure F-3. Extinction length vs. wavelength based on NRaD model.

3.1.4 Divergence

The 20-μm wide delivered laser diodes did not meet Titan's original specifications in that the 14-degree parallel far field divergence angle was 4 degrees wider than specified.

3.1.5 Tuning Range

The tuning range (23 to 26 nm wide) was slightly less than the original 28-nm range (not including low temperature stability and high temperature modulation problems). The subcontractor (Sarnoff) has proposed design modifications that may increase the tuning range.

3.2 DEMONSTRATION

Titan demonstrated an IR link outdoors during the final review. All hardware were powered by AC lines. The 20-μm-wide lasers (DH731B # 12, 16 and 80, similar to proposed Phase II laser array elements) were not used due to spatial beam profile problems. A 7-μm wide laser (DH756-1 #10) with a smooth spatial profile characteristic was used for all outside testing. Despite the benefit of a better profile, these smaller width lasers were unable to maintain the required 100-mW average power levels at a temperature of +50 degrees C.

3.2.1 Data Rate

The laser diode was pulsed at a rate of 50 kHz due to the limited bandwidth of the op amps (Analog Devices 743) in the receiver. The receiver was positioned approximately 70 meters away from the laser transmitter.

Since no modem was built (to be built in Phase II), no real data were sent through the link. There was also no quantitative bit-error-rate (BER) testing.

3.2.2 LOS

This link is strictly LOS. When someone walked in the area between the transmitter and receiver, the link was lost whenever he strayed into the beam path. Previous testing also showed no detectable signal when the direct path between the transmitter and receiver was blocked.

Previous tests indicated that the receiver signal was strong with acceptable signal-to-noise-ratio (SNR) out to 5 degrees from the boresight of the laser transmitter, provided no obstacle existed between the transmitter and the receiver.

3.3 MODEL

Titan used its Algorithm for Evaluating System Operations Performance (AESOP) to calculate single and multiple scattered signal components, background and system noise currents, and electrical power SNR at the receiver as a function of the IR transmitter system parameters. The theoretical results did not match the outdoor experimental tests, perhaps due to unpredictable wavelength changes (most likely caused by thermal effects).

3.4 PHASE II PLAN

Titan provided the Government with a <u>Plan for Phase II of Short-ranged Infrared Laser Communication</u> that covered the work to be performed during a Phase II effort. The proposed plan

would incorporate two laser diode arrays based on a 20-μm ridge width and 700-μm cavity length multiple-quantum-well (MQW) design that would provide up to 2 W of average power at a 2-MHz rate. Ten receivers would be assembled into one detector assembly. Titan would also incorporate (with approval) a Multiple Rate VoCoder (MRVC) to provide voice and data one-way link with a 2-Mpbs demonstration at two sites (Camp Pendleton, California and a DOE test range southeast of Albuquerque, New Mexico).

4.0 CONCLUSIONS

The Titan system has the potential of providing a high-data-rate link, on the order of 2 Mbps, to support high-data-rate ISRC missions. The system provides a rugged, all-solid-state design with low power consumption and many commercially available parts.

4.1 NLOS

The diode lasers manufactured in Phase I met the ≥5 degree off-boresight axis BAA requirement, but demonstrated no NLOS capability. There was no reception of signal when the direct path between the transmitter and receiver was blocked. Further investigation and calculations into the atmospheric scattering characteristics for IR radiation around the 1.39-μm peak are recommended.

4.2 BEAM PROFILE

The design for a 100-mW, 20-μm wide laser with center frequency of 1.335 μm apparently has an inherent spatial beam profile problem. This yields an irregular dependence of the off-boresight angle on the propagation distances.

4.3 LINEWIDTH

The specifications of ≤10-nm linewidth is too broad for a tunable range of ±13 nm. It may be difficult to provide a narrow-linewidth single-mode laser at the average power levels needed to maintain connectivity over the desired range. Temperature instability, inconsistent spectral profile, and varying atmospheric conditions all contribute to the problem of determining a realistic tuning scheme for a system based on 1.33-μm laser diodes.

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The U.S. Marine Corps (USMC) desired to develop short-range communications links whose ranges are intentionally limited to very short distances. These links support tactical missions such as LAN Backbone, Wideband Data Link, and Company Radio.

The short-range limitation arises from the need for low probability of detection and intercept (LPD/LPI). Since the detection of an undecipherable transmission would still provide an enemy with information regarding transmitter location and allow him to take countermeasures, the Marine Corps Systems Command (MARCORSYSCOM) is sponsoring the development of technologies that can be LPD by their very nature.

The Intentionally Short-Range Communications (ISRC) project at the Naval Command, Control and Ocean Surveillance Center (NCCOSC) RDT&E Division (NRaD) is pursuing feasibility studies for these USMC missions based on such technologies as ultraviolet (UV) lamps, UV lasers, infrared (IR) lasers, millimeter waves (MMW), and direct sequence spread spectrum (DSSS) at radio frequencies.

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